TURLEY, Jr.

Bond Stress in Reinforced Concrete Beams

Theoretical and Applied Mechanics

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BOND STRESS IN REINFORCED CONCRETE BEAMS

BY

ROBERT EDGAR TURLEY, JR.

B. S. University of Illinois, 1913.

THESIS

Submitted in Partial Fulfillment of the Requirements for the

Degree of

MASTER OF SCIENCE

IN THEORETICAL AND APPLIED MECHANICS

IN

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OF THE

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THE GRADUATE SCHOOL

June 5, 1915

I HEREBY RECOMMEND THAT THE THESIS PREPARED UNDER MY SUPERVISION BY ROBERT EDGAR TURLEY, JR.

ENTITLED BOND STRESSES IN REINFORCED CONCRETE BEAMS.

BE ACCEPTED AS FULFILLING THIS PART OF THE REQUIREMENTS FOR THE DEGREE OF MASTER OF SCIENCE IN THEORETICAL AND APPLIED MECHANICS.

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Head of Department

Recommendation concurred in:*

Committee on Final Examination*

*Required for doctor's degree but not for master's.

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I.

INTRODUCTION.

BOND STRESS IN REINFORCED CONCRETE BEAMS.

I. INTRODUCTION.

Preliminary:- Plain concrete has a limited use as a structural material since it is effective only in resisting compressive stresses. Steel rods have been embedded in plain concrete in order to make the material effective in resisting flexural stresses. This combination of concrete and steel, commonly called reinforced concrete, is so arranged that the principal compressive stresses are resisted by the concrete and the tensile stresses are resisted by the steel. Before this combined action can take place, there must be a permanent and dependable adhesion or bond between the concrete and steel.

Therefore, because of the importance of bond resistance, this subject has received much attention and numerous bond tests have been made. These tests have been conducted under a wide range of conditions, and as would be expected, the results show considerable variation. Naturally there exists a diversity of opinions among concrete designers as to the source and nature of bond resistance. The nature of bond resistance in simple beams with straight bars and having no web reinforcement is well understood. However, the use of stirrups, bent up bars, and end anchorage, introduces complications which prevent a rational mathematical analysis. Again, there are instances where too much confidence has been placed upon the bond resistance of deformed bars. The tests herein described were undertaken with a view that they would help to clear up a few of the

hazy ideas on bond resistance.

2. Scope of Investigations:- Tests were made on 38 reinforced concrete beams, 66 pull-out specimens, 48 8 x 16-inch compression cylinders, 6 6-inch cubes, and 3 control beams. Tension tests were made on 3 specimens of each size and kind of the steel reinforcing bars to determine the yield point of the material.

The beams were designed so as to insure bond failure. In twenty-two of the beams, the longitudinal reinforcement consisted of a single bar of large diameter placed horizontally throughout the length of the beams. Two beams were reinforced with a single bar with the ends anchored by 90° bends over the center of the supports. Four beams were reinforced with a single bar bent up between the load points and the supports. Four beams were reinforced with two bars, one straight and one bent up. Two beams were reinforced with a single straight bar and vertical stirrups, this group being the only one having web reinforcement other than bent up bars.

The most interesting features of this investigation are the time tests. In these tests, beams were kept under a continued load for longer periods of time than in any previous tests in the laboratory. The slip of the ends of the reinforcing bars and the deflection at the center of the beams were measured each day. In one test the change in the width of a crack during a period of six days was measured.

Other phases of bond resistance included in the tests are the effect on bond due to the difference in the density of

the concrete at the top and bottom of the beam, and the effect of settlement of the concrete away from a restrained bar. In all cases accurate measurements of the slip of the ends of the bars were made. Both plain and deformed bars were used in order to bring out the action of the deformed bar as contrasted with the plain bar.

The pull-out tests consisted in applying load to a short reinforcing bar embedded axially in a cylindrical block of concrete eight inches in diameter and eight inches long. For each size and type of bar used in the beam tests, pull-out tests were also made. The pull-out tests serve as a comparison of the relative bond resistance found in this type of specimen and in beams.

The cubes, cylinders, and control beams were made from the same batch of concrete as the beams having the same number, and serve as an indication of the quality of the concrete in the beams. Extensometer readings were taken on one cylinder from each batch in order to determine the modulus of elasticity of the concrete.

3. Acknowledgment:- The tests reported herein were made in the Laboratory of Applied Mechanics of the University of Illinois as part of the work of the Illinois Engineering Experiment Station in the subject of reinforced concrete. The work was done under the direction of Professor A. N. Talbot, in charge of the Department of Theoretical and Applied Mechanics, whose suggestions were very helpful in planning the tests and in working up the data. The writer is indebted to Mr. H. F.

Gonnerman, First Assistant in the Engineering Experiment Station, for the interest taken and the assistance given in performing the tests. Mr. J. O. Draffin, Research Fellow in the Engineering Experiment Station, also gave valuable assistance in the testing work.

II.

ANALYSIS AND THEORY.

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ANALYSIS AND THEORY.

4. Stresses in a Reinforced Concrete Beam:- The following discussion is applicable only to simple beams with perfect freedom from end restraint. This condition existed in these tests, where the ends of the beam were supported on steel plates free to revolve on steel rollers.

In the analysis of beam action, the stresses are divided into two general classes; (1) longitudinal tension and compression, and (2) vertical, horizontal, and inclined shearing stresses, and diagonal tensile and compressive stresses. In steel or wooden beams the stresses in the second class are generally of secondary importance when calculating the load carrying capacity of the beam, but in the reinforced concrete beams due to the low tensile strength of the concrete, the strength of the beam is frequently limited by its inability to resist these stresses. The advent of reinforced concrete introduced the term bond stress which may be classed with the second type of stresses commonly called web stresses. Bond stress may be defined as the resistance to slip of the reinforcing bar in the concrete.

5 Notation:- The standard notation used by the Engineering Experiment Station and by most writers on the subject of reinforced concrete will be used. Reference may also be made to Figure 1.

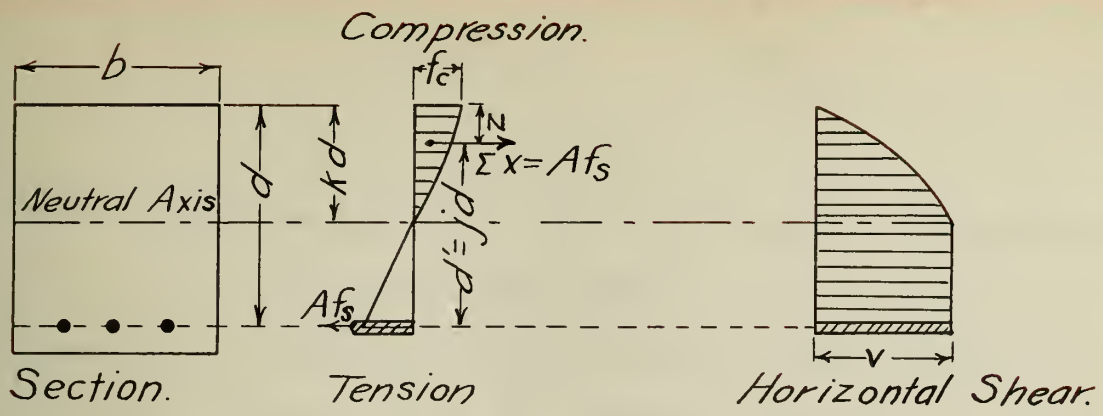

Figure 1.
Distribution of Stresses Over Cross-Section of Beam.

b = breadth of beam.

d = distance from the compression face to the center of gravity of the cross-sectional area of the reinforcing steel.

A = are of cross section of longitudinal reinforcement.

$p = \frac{A}{bd}$ = ratio of area of metal reinforcement to area of concrete above center of reinforcement.

o = periphery of one reinforcing bar.

m = number of reinforcing bars.

E_s = modulus of elasticity of steel.

E_c = initial modulus of elasticity of concrete in compression.

$n = \frac{E_s}{E_c}$ = ratio of two moduli.

f_s = unit tensile stress in metal reinforcement.

f_c = unit compressive stress per unit of area in most remote fiber of concrete.

d^1 = distance between the centers of gravity of the metal reinforcement and the compressive stresses.

j = ratio of d^1 to d. $d^1 = jd$.

M = resisting moment at the given section.

u = bond stress per unit of area on the surface of the reinforcing bars.

v = vertical and horizontal shearing stress per unit of area in the concrete.

6. Beams Without Web Reinforcement: Bars Straight:-

(a) Resisting Moment:- In the straight line formula for the calculation of the resisting moment of a reinforced concrete beam, the tensile resistance of the concrete is neglected. This assumption is correct for only one condition, that is when a vertical tensile crack has formed at the section under consideration and extends from the tension face of the beam to the neutral axis. At any other section where the concrete is not cracked this formula is grossly in error and it is necessary to consider the tensile stress in the concrete in order to arrive at the true relations. Referring to Figure 1, the expression for the resisting moment is

$$M = Af_s d^1 = Af_s jd \text{---- (1)}$$

Since $p = \frac{A}{bd}$, then

$$M = f_s pjbd^2 \text{ ---- (2)}$$

(b) Bond Stress:- When a reinforced concrete beam deflects under load, the horizontal fibers in the tension portion of the beam elongate. Due to the adhesion or bond of the concrete surrounding the reinforcing bars, this tensile elongation is transmitted to the reinforcing steel. Referring to Figure 2, it is seen that the bending moment and consequently the tensile stress to be transmitted from the concrete web to the steel vary from the centre of the beam to the end. This increment of stress between adjacent sections of the reinforcement must be taken off by the bond of the surrounding concrete, and, in so doing, there is developed a tendency of

the rods to slip in the concrete. The total bond developed on the surface of the bar per unit length is equal to the total change in the tensile stress of the bar per unit length.

The following derivation of the formula for bond stress in beams, in which the reinforcement is continued straight to the ends of the beam, is taken from Bulletin No. 29 of the Engineering Experiment Station. The longitudinal tensile strength of the concrete is neglected. From equation (1), the resisting moment is found to be

$$M = Af_s d^1$$

Differentiating this equation

$$\frac{dM}{dx} = A \frac{df_s}{dx} d^1$$

By the principles of mechanics of beams,

$$\frac{dM}{dx} = V,$$

where V is the total vertical shear at the section

Substituting and transposing

$$\frac{Adf_s}{dx} = \frac{V}{d^1} \quad \text{--- (3)}$$

The derivative $\frac{Adf_s}{dx}$ expresses the rate of change of the total tensile stress in the reinforcing bars, and measures what is transmitted to the concrete by bond. Using m as the number of bars, o as the periphery of one bar, the total surface of bars per unit length is mo and the bond stress developed is mou, where u is is the bond stress per unit of area of surface of bar. Equating this to the value of the derivative in equation (3),

$$u = \frac{V}{mod^1} \quad \text{--- (4)}$$

which is the formula for the bond stress developed in beams having the reinforcing bars straight throughout their length.

(c) Shearing Stresses:- The following derivation of the formula for shearing stress is taken from Bulletin 29 of the Engineering Experiment Station. It is shown in texts on the mechanics of materials that there exixts at all points in a beam vertical and horizontal shearing stresses. At any point in a beam the vertical shearing unit stress and the horizontal shearing unit stress are of equal intensity. This horizontal shear is necessary for the transferrence of the increments of stress from the tensile reinforcement to the compressive side of the beam. The amount of this stress increment transmitted from the reinforcing bars per unit of length is by equation (4)

$$mou = \frac{V}{d^{I}}$$

Consider this distributed over a horizontal section just above the reinforcing bars for a unit length of beam. Let v = the horizontal shearing unit stress. The shearing resistance per unit of length of beam is then bv, and equating this to mou,

$$v = \frac{V}{bd^{I}} \quad \text{----(5)}$$

Figure 1 shows the distribution of the horizontal shearing stress over a vertical section when the tensile strength in the concrete is zero. The shearing stress as given by equation (5) may vary from 13% to 25% more than the average shearing stress considered uniformly distributed over a vertical section.

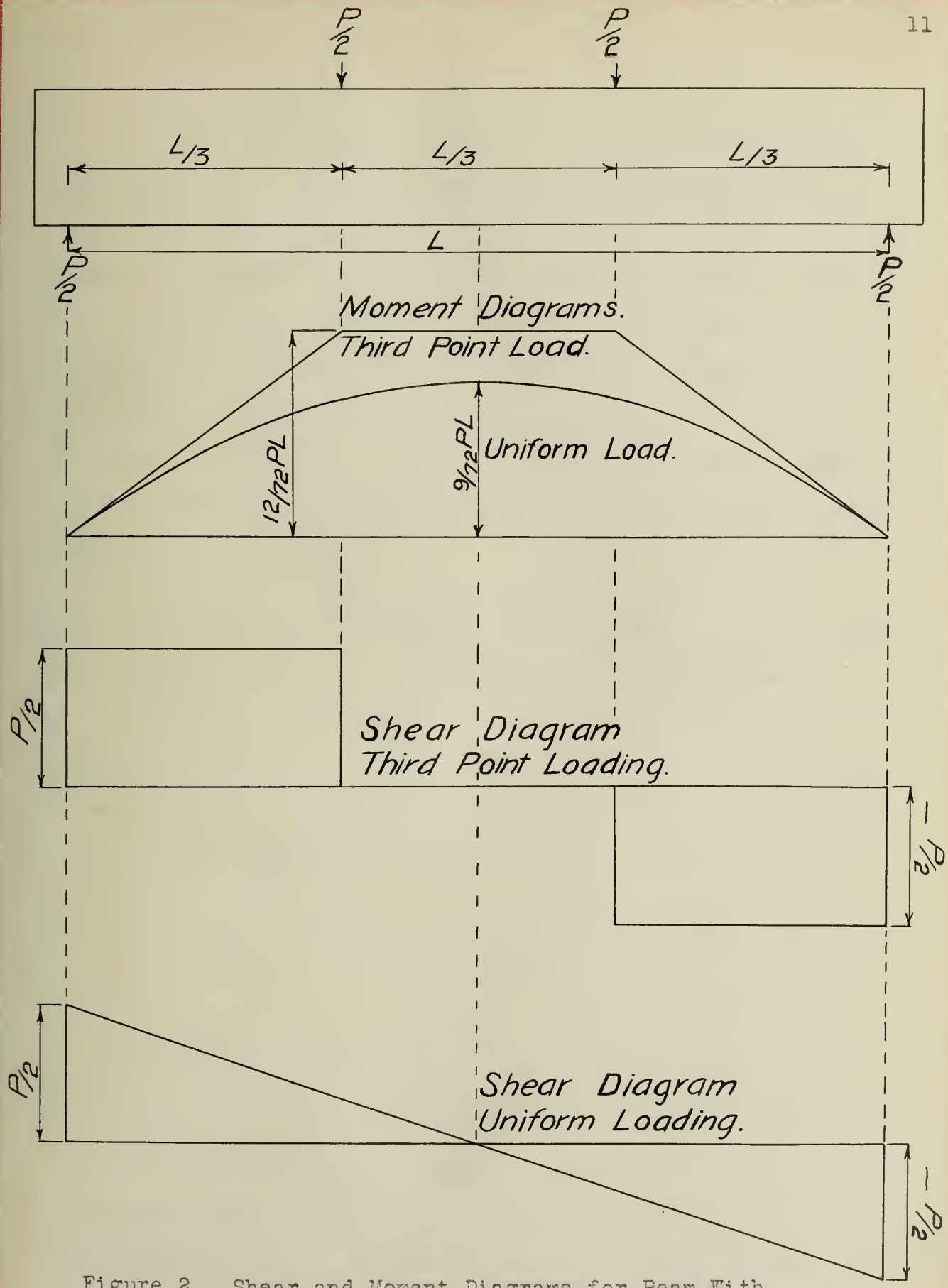

Figure 2. Shear and Moment Diagrams for Beam With Uniform and Third Point Loading.

7. Bond Stress in Beams without Web Reinforcement: Bars Bent Up:- When all or part of the reinforcing bars are bent up to take diagonal tensile stresses, the formula for bond stress as derived in Art. 6 is no longer applicable. Because of the complications which are introduced by bent up bars, it is impossible to deduce an analysis which will be applicable to all cases. However, the following discussion will indicate in a general way the stress distribution which exists in beams with bent up bars, and the variation from the conditions in beams with all bars straight.

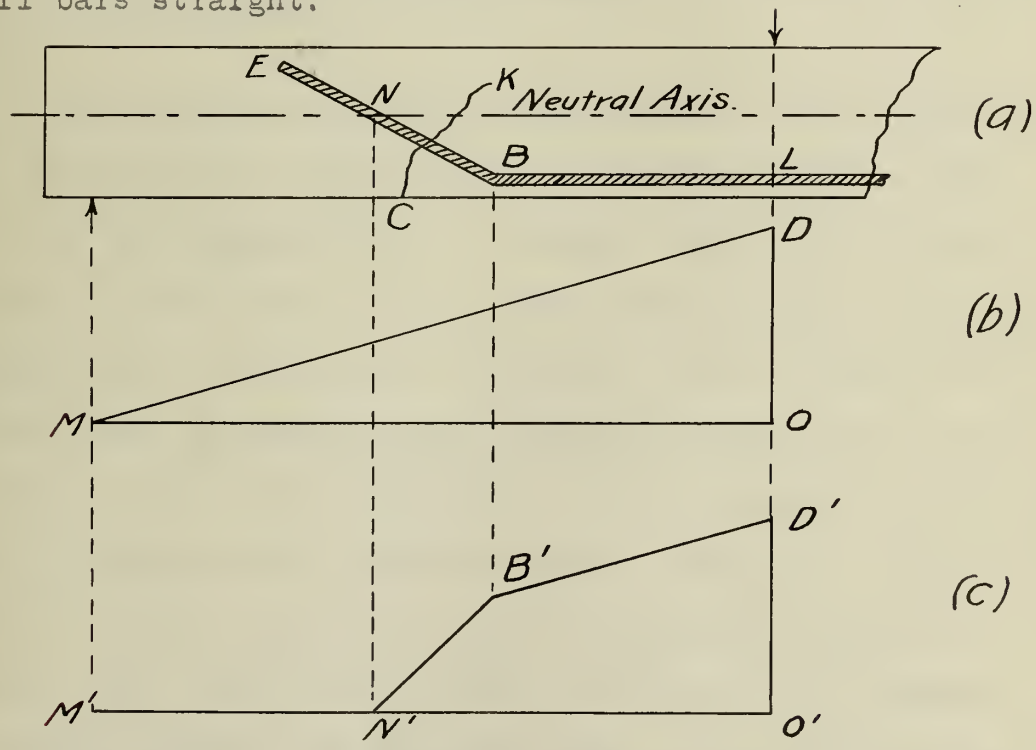

Figure 3. Distribution of Bond Stress in Beam with All Bars Bent Up.

Figure 3 (a) represents the outer third of a beam loaded at the third-points, and in which all the reinforcing bars are bent up at B. Figure 3 (b) is a moment diagram for the outer third of the beam, the vertical ordinate between the

lines MO and MD at any point being the value of the external bending moment at that point. In a beam with all bars straight, this ordinate at any point will also represent the theoretical value of the total tensile stress in the steel at that point, provided the proper scale is selected and the tensile stress of the concrete is neglected. Since the difference in the value of any two ordinates is the increment in tensile stress to be taken off by bond in the distance between these ordinates, the slope of the line MD will represent the distribution of the bond stress on the reinforcing bars throughout the outer third of the beam.

Now consider the condition where all the bars are bent up at B and cross the neutral axis of the beam at N. First assume that the crack CK has not formed. At B the stress in the steel will be the same as in the case with all bars straight, but at N there will be no stress in the steel due to beam action. This means that the total tensile stress in the steel must be taken off by bond in the length BN, and the result will probably be local slipping of the reinforcing bar along BN. Figure 3 (c) represents a steel stress and bond distribution diagram for this condition. The bond stress on the bars from L to B remains unchanged as indicated by the line B^1D^1, but from B to N a higher bond stress exists as shown by the slope of the line N^1B^1. From a vertical section through the beam at N to the end of the beam, the concrete alone must resist all tensile stresses in the tension side of the beam.

When crack CK forms, the conditions are again changed.

A high tensile stress is thrown into the reinforcing bars where crossed by the crack. This action relieves the high bond stress on the bars from the crack to B, but the total stress in the steel at the crack must be taken off by bond from the crack to the end of the bars at E. If there is not sufficient embedment of the bars from the crack to E, or if the end of the bar at E is not anchored, the bars will pull out of the concrete causing the beam to fail.

Figure 4 (a) represents the outer third of a beam loaded at the third points, and in which part of the bars are bent up. By the selection of the proper scales, both the total tensile stress in the steel and the external bending moment at any point in the outer third of a beam with all bars straight will be given by the ordinate to the line DBA at that point. The

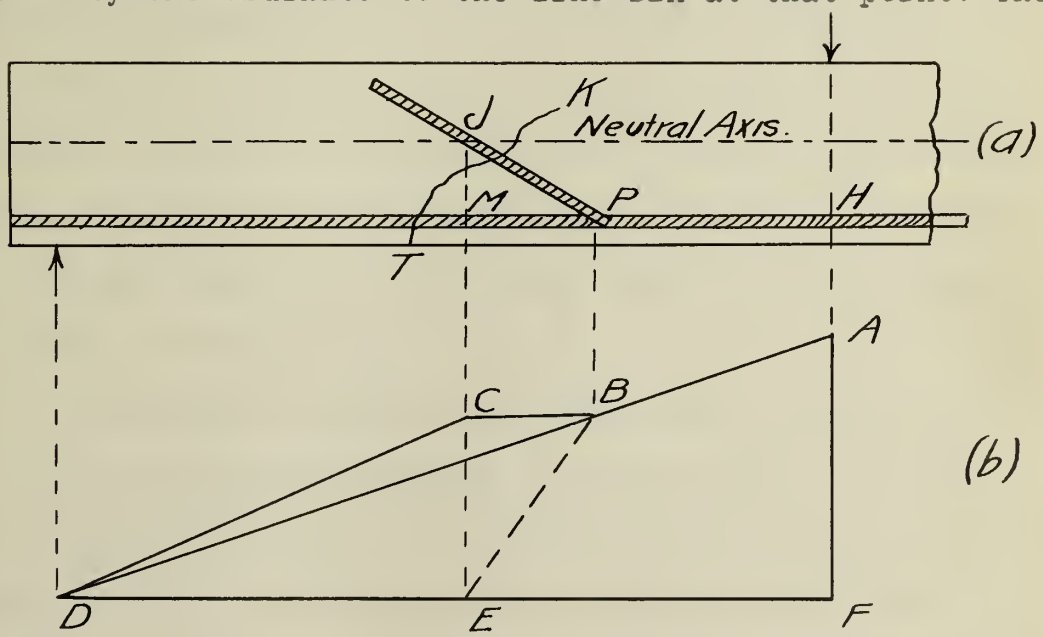

Figure 4. Distribution of Bond Stress in Beam with Part of Bars Bent Up.

slope of the line DA will represent the distribution of the bond stress.

First consider the case before the diagonal crack TK has formed. Part of the rods are bent up at P and cross the neutral axis of the beam at J. The distribution of the bond stress will remain unchanged from H to P in either the straight or bent up bars. In the bent up bars, as was the case with all bars bent up, the total stress at P must be taken off by bond in the length PJ, and the line ABE (Figure 4 (b)) will represent the bond distribution for the bent up bars. At the point M in a vertical plane which passes through the intersection of the bent up bars with the neutral axis of the beam, all the tensile stress that existed in the bent up bars has been transferred through the concrete from these bars into the straight bars. The tensile stress in the length PM of the straight bars will be nearly constant or may even increase from P to M, resulting in a low bond stress, or even a reversal in direction of the bond stress along PM. From M to the end of the beam the bond stress will be higher than the value given by the formula for all bars straight. The distribution of the bond stress is represented by the line ABCD, Figure 4 (b).

If a diagonal tension crack TK crosses the bent up bars, the same conditions will exist in these bars as in the case with all bars bent up. In the straight bars, at the point of intersection with the crack, a high tensile stress will be concentrated in the steel which must be taken off by bond from the crack to the end of the beam.

8. Bond Stress in Beams with Web Reinforcement:-

The use of web members introduces additional com-

plications into the phenomena of bond stress. Three classes of web reinforcement will be considered, (1) loose vertical stirrups, (2) rigidly attached vertical stirrups, and (3) inclined web members.

By loose vertical stirrups is meant any type of vertical web reinforcement which engages the horizontal steel but is free to slip along the longitudinal bars. Since vertical web reinforcement does not come into action until the concrete web is ruptured in tension, it is not to be expected that this type of web reinforcement will have any effect upon the first slip of the ends of the reinforcing bar. If end slip occurs in a beam without web reinforcement, a diagonal tensile crack in the concrete generally opens up and causes sudden failure of the beam. Vertical stirrups will take this diagonal tension and the beam will carry a higher load before failure occurs. Thus it is seen that the use of vertical stirrups increases the vertical shear that may be developed and consequently increases the calculated bond stress on the longitudinal bars.

When the vertical stirrups are rigidly attached or welded to the longitudinal bars, each stirrup acts as an anchor for the horizontal steel, and the slip of the bars can not become large without shearing off the stirrups or crushing the concrete in front of the stirrups. A high shear and consequently a high bond stress will be developed before this shearing action can take place.

With inclined web members, the horizontal component of the stress in the stirrup at its connection with the longitudinal bars is transferred into the bars, and this action

has a tendency to make the stress in the bars constant throughout their length. This reduces the bond stress on the bar and a higher load is carried before a bond failure will occur. Thus, it is evident that the use of either vertical or inclined web members stiffens the beam and prevents a failure by diagonal tension as soon as the longitudinal bars slip. This increases the total vertical shear V at failure and thereby increases the calculated bond resistance.

9. Variation in Bond Stress in Beams with Uniform and Concentrated Loads:- In practice, beams are generally deisgned for loads assumed uniformly distributed over the length of the beams. It is impracticable to reproduce this condition in laboratory tests, and the method of loading with two equal concentrated loads applied at the third points is generally adopted. Figure 2 shows the moment and shear diagram for a load P uniformly distributed over the span length L, and applied in two equal concentrated loads at the third points of the beam. From the figure, it is seen that the greatest bending moment occurs in the case of the third point loading. There is no bond stress due to beam action between the loads with third point loading, and the bond stress is uniform throughout the outer thirds of the beam. With uniform loading, the bond stress varies from zero at the center of the beam to a maximum value at the ends of the beam.

III.

MATERIALS, TEST PIECES, APPARATUS AND METHODS OF TESTING.

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MATERIALS, TEST PIECES, APPARATUS, AND METHODS OF TESTING.

10. Concrete Materials:- The concrete materials used in making the test pieces were the same as those used for other concrete and reinforced concrete specimens made and tested by the Engineering Experiment Station in the past. The quality of the materials was equal to that used in first-class concrete construction throughout the middle west.

(a) Cement:- Universal portland cement was used. The results of briquette tests of two samples of this cement are given in Table I. All cement tests were made by Mr. B. L. Bowling, Assistant in Charge of Cement Laboratory, University of Illinois.

TABLE 1.

Briquette Tests of Cement.

Standard Ottowa sand was used in the 1-3 briquettes. The results are expressed in pounds per square inch.

	Neat		1-3	
No.	7 days	28 days	7 days	28 days
1	510	670	180	315
2	510	640	175	320
3	520	660	190	305
4	510	655	180	305
5	520	640	210	275
Average	514	653	187	304
1	505	675	160	275
2	510	690	155	290
3	500	685	170	260
4	510	635	175	290
5	-	640	175	290
Average	506	665	167	276

(b) Sand:- The sand came from near the Wabash River at Attica, Indiana. Fineness tests of samples of the sand are given in Table 2. A set of briquettes made from the sand using Universal cement gave values about 15% higher than the standard sand. The sand was coarse and well graded.

TABLE 2.

Mechanical Analysis of Sand.

Sieve No.	Separation Size Inches	Percent passing each sieve. Sample No. 1	Sample No. 2	Sample No. 3	Average
3	0.28	100	100	99.8	99.9
5	.174	87.8	85.9	89.8	87.8
10	.091	56.5	55.9	66.2	59.5
12	.067	49.6	48.6	58.7	52.3
16	--	42.9	42.3	53.3	46.1
18	.043	34.4	33.7	44.3	37.5
30	.027	22.0	20.9	29.8	24.2
40	.019	10.3	9.1	15.9	11.8
50	.013	4.3	3.7	8.0	5.3
74	.009	2.7	2.0	5.5	3.4
150	--	1.2	0.9	2.3	4.4

(c) Stone:- The crushed limestone came from Kankakee, Illinois. It had been screened through a one-inch screen and over a 1/4-inch screen. Mechanical analysis of a number of samples of this stone are given in Table 3. It contained from 45 to 50% voids.

TABLE 3.

Mechanical Analysis of Stone.

Size of Square Opening	Separation Size Inches	Percent Passing Each Sieve. Sample No. 1	Sample No. 2	Sample No. 3	Average
1-inch	----	98.0	100	100	99.3
3/4 inch	----	96.8	96	95.6	96.1
1/2 inch	----	65.9	56	69.9	63.9
3/8 inch	----	44.3	36.2	47.9	42.8
No. 3	0.280	25.6	21.8	31.7	26.3
No. 5	.174	5.9	5.9	5.6	5.8
No. 10	.091	3.9	4.4	3.1	3.8

11. Concrete:- The concrete was proportioned by loose volume, the materials being measured in buckets. The materials were weighed also in order to obtain an independent check on the proportions. A 1-2-4 mixture was used exclusively.

The work of mixing and placing the concrete was done under the direct supervision of Mr. H. F. Gonnerman, by men of considerable experience in concrete work. The mixing was done in a 9-cu. ft. Marsh-Capron Batch-mixer. The stone and sand and about one-half the water were placed in the mixer drum in the order named, while running at full speed of about 22 revolutions per minute, and then the cement and the remainder of the water were admitted. Each batch was mixed for 5 minutes after adding the cement, and when this operation was completed, the batch was discharged onto the concrete floor and removed to the forms by means of a wheelbarrow.

12. Reinforcing Steel:- Both mild and high carbon steel were used. All the plain round bars were of mild steel. The twisted square bars were of mild steel, but tension tests on specimens of this type showed no well defined yield point. The corrugated and Havemeyer bars were of high-carbon steel. See Table 4 and Figure 9 for details of the reinforcing bars. The results of tension tests on three specimens of each size and type of bar are given in Table 5. All bars were more or less rusty.

TABLE 4.

Notes on Reinforcing Bars.

Bar	Equivalent Section	Perimeter Inches	Remarks
3/4-inch plain round		2.356	
1-inch plain round		3.142	
1 1/8-inch Corrugated round	Round Bar	3.534	Circumferential corrugations 0.09 in. high, 1.6 in. apart.
1-inch Square Havemeyer.	1-in. square	4.00	See Figure 9
1-inch Twisted Square	1-in. square	4.00	Cold Twisted; 1 twist per lin. ft.

TABLE 5.

Tension Tests of Reinforcing Steel

Loads are in lbs.- Stresses in lbs. per Square Inch.

No:	Bar	Load Yield Point	Load Ultimate	Unit Stress Yield Point	Unit St. Ultimate
1:	3/4-in plain round	16550	24520	37600	55300
2:		16410	24300	37100,	54900
3:		16800	24380	38000	55100
Average				37560	55100
1:	1-in plain round	26000	---	33100	---
2:		25060	---	31900	---
3:		25380	---	32300	---
Average				32400	
1:	1 1/8 in Corrugated round	50870	86000	51200	86500
2:		55510	---	55800	---
3:		55170	---	55400	---
Average				54100	
1:	1-in square Havemeyer	46650	---	46650	---
2:		59490	---	59490	---
3:		42570	---	42570	---
Average				49570	
1:	1-in twisted square		74860	---	74860
2:			64970	---	64970
3:			72900	---	72900
Average					70900

13. Reinforced Concrete Beams:- All of the beams and auxiliary test pieces were made of 1-2-4 concrete. Beams No. 1 to 8 inclusive; No. SC1, SC4, and SC7, No. 1091, 1092, 1093, and 1094 were 8 by 12 inches in section. All other beams were 10 by 12 inches in section. The length was $6\frac{1}{2}$ feet in all cases, with a test span of 6 feet from c. to c. of supports. With the exception of 1086.1 and 1086.2, the ends of the bars were squared and extended flush with the ends of the beam. In twenty-six of the beams, the longitudinal reinforcement consisted of a single straight bar placed in the middle of the width of the beam. In all of the beams, the center of the reinforcing rods was 10 inches below the top of the beam. Only four beams, 1091 to 1094 inclusive, had web reinforcement. These beams were reinforced with loose vertical stirrups of 1/4-inch plain round bars placed 4 inches apart throughout the outer thirds of the beam. The stirrups, which were V-shaped, engaged the longitudinal reinforcement with one complete turn, and extended to within 3/4 inch of the top surface of the beam and were bent downward and inward. See Figure 5 p. 25 to 28 inclusive for details of the beams.

The beams were made in wooden forms directly on the concrete floor of the laboratory, a sheet of building paper having been placed under the form. Enough concrete was mixed in each batch to make one beam and the corresponding auxiliary specimens. Beams No. 1095.1 and 1096.1 were made from two batches discharged together on the concrete floor of the laboratory. Beams No.1095.2 and 1096.2 were also made from two

batches discharged into one pile. The reinforcing steel was placed in position and held at the proper elevation by means of corks. The forms were wet down, and filled in layers of about 3 inches depth. Each layer was troweled along the inner sides of the forms to insure a smooth surface. The concrete was mixed rather wet so that little tamping was necessary after placing it in the forms. The forms were removed in four days, at which time the beams were covered with wet burlap until one week old. When one week old, the beams were removed from the floor where they were made and stacked up in tiers four deep over a 6 inch bed of wet sand. The beams were covered with burlap and wet down morning and evening. When seven weeks old, the beams were hauled to the testing laboratory and allowed to dry out for seven days before being tested. Figures 29 to 32 inclusive show the daily variation in temperature and hygrometer readings in the storage room.

14. Auxiliary Specimens.

(a) Pull-out Specimens:- The pull out specimens were cast in a vertical position with the bar projecting about 18 inches below and 1/4 inch above the concrete block. Metal forms were set up on a platform slotted to allow the bar to extend below the bottom. A planed cast-iron base plate made the bottom of the form for the concrete block. The bar passed through a central hole in the base plate. A strip of building paper was placed on the plate. Generally the batch was removed to the forms in three wheelbarrow loads. One pull-out specimen was

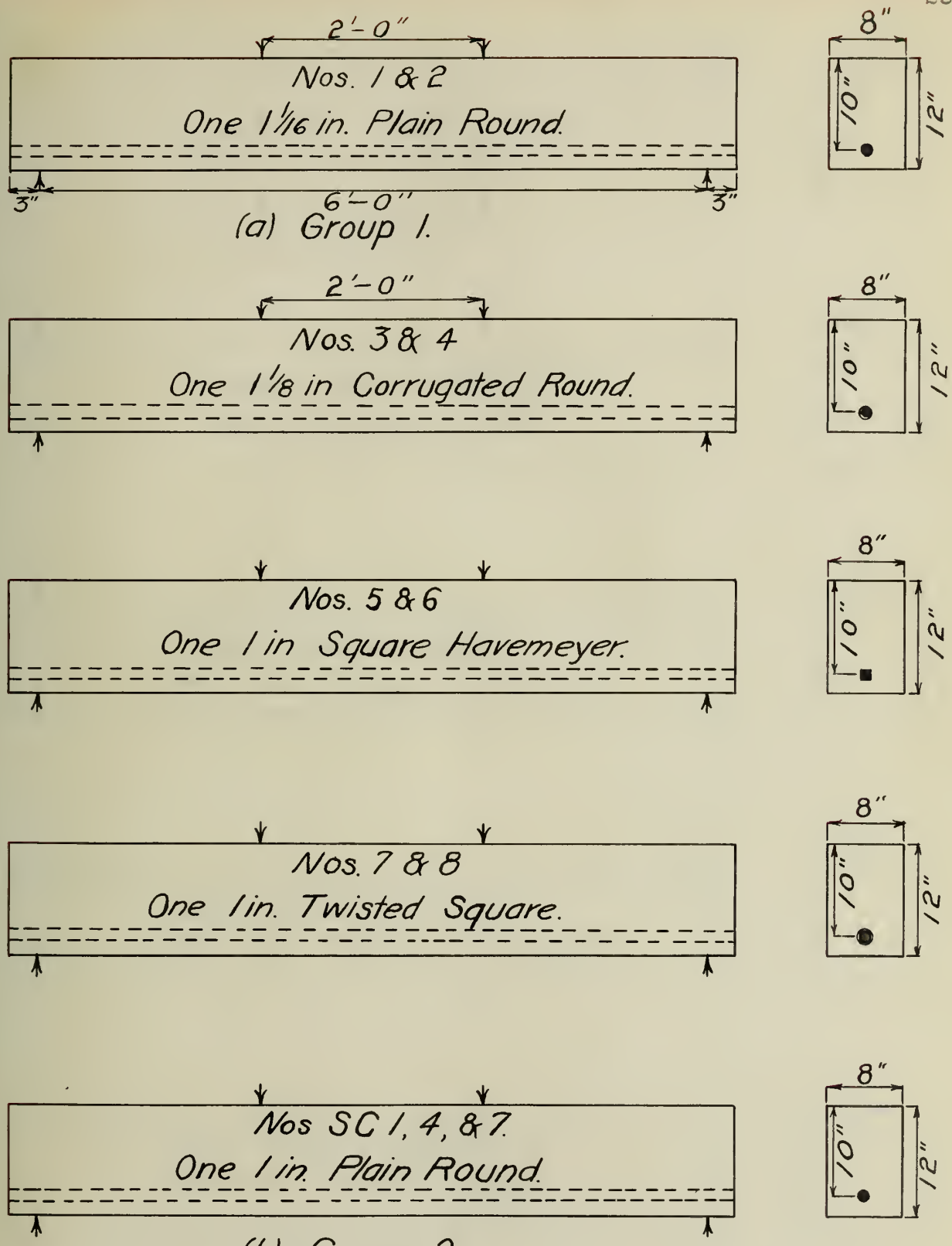
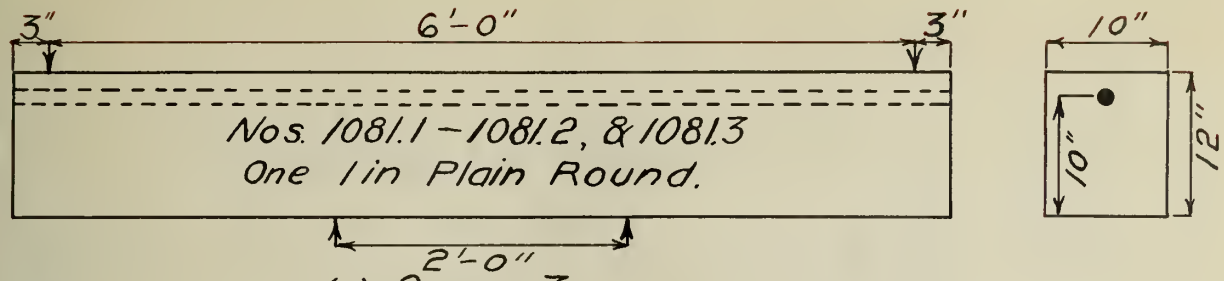
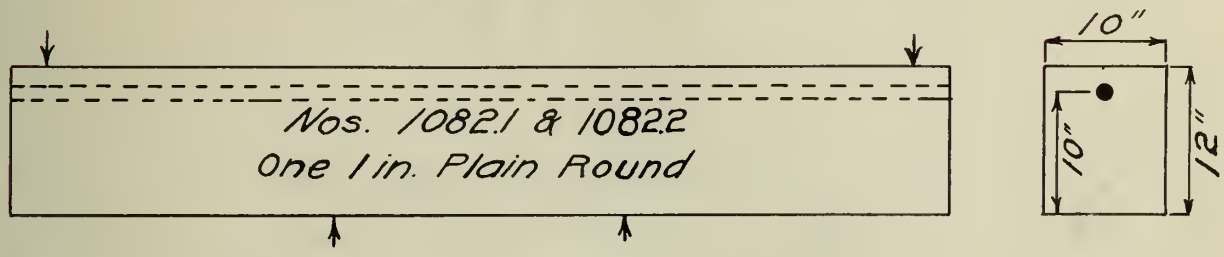


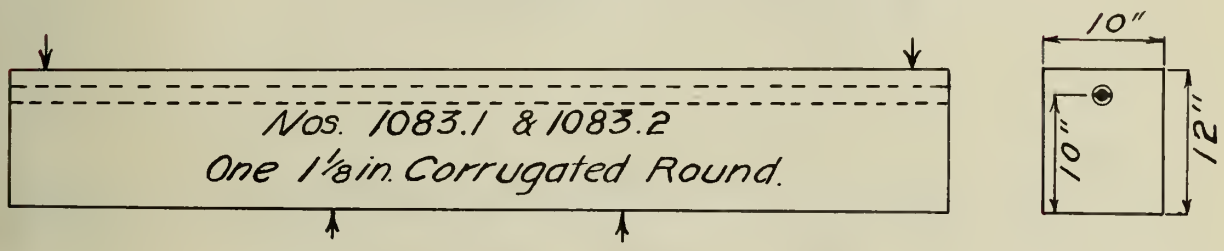
Fig. 5.

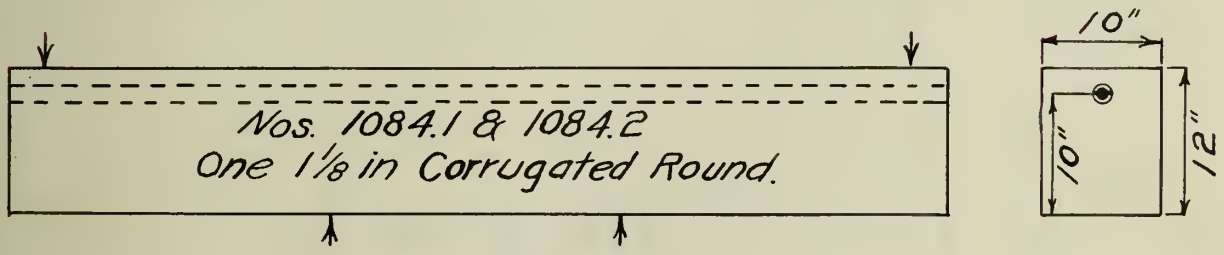
Details of Reinforced Concrete Beams.

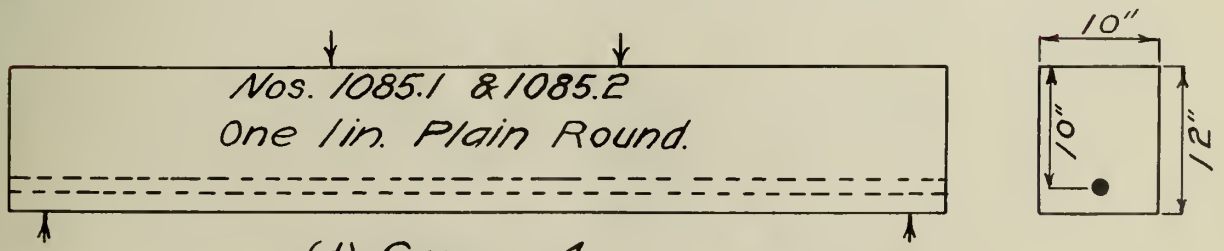


(c) Group 3.

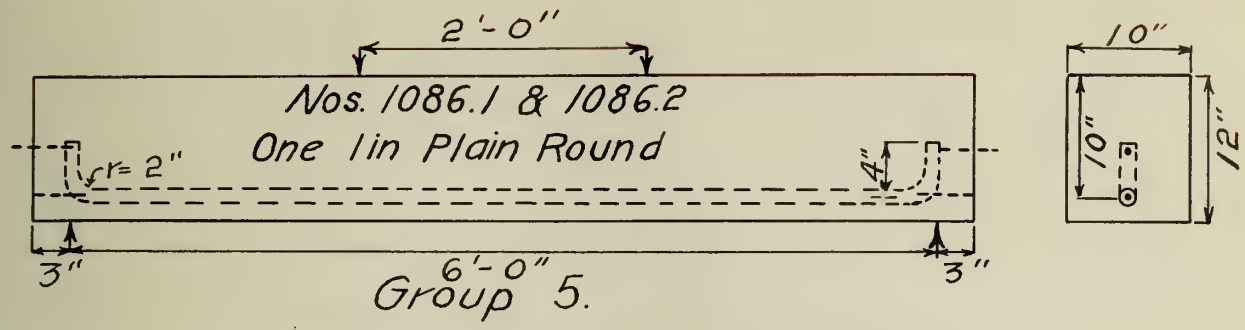


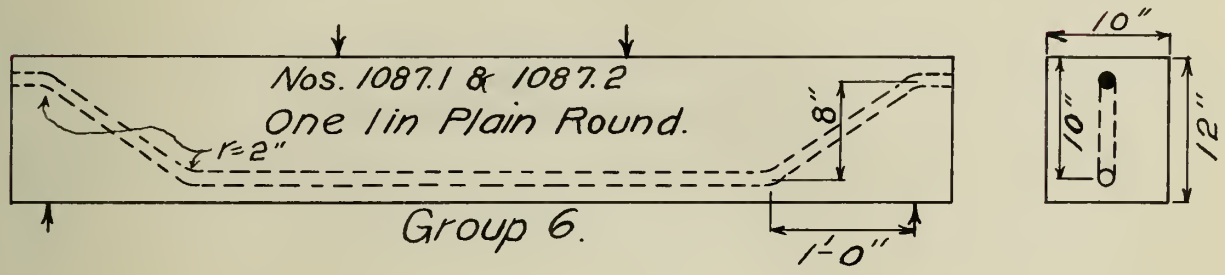


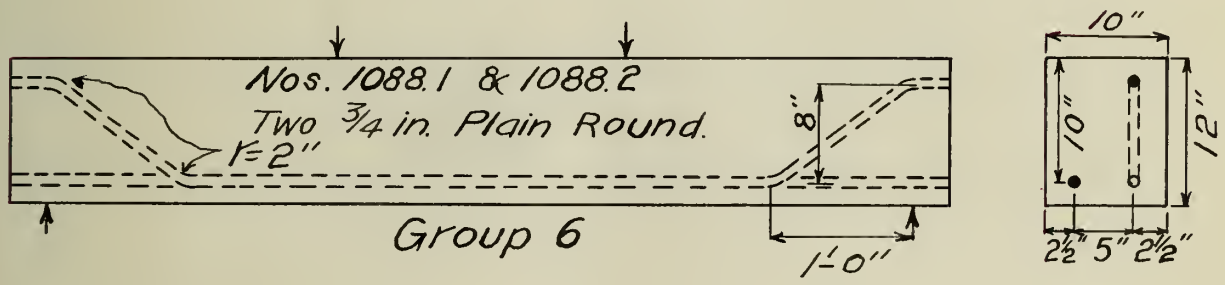


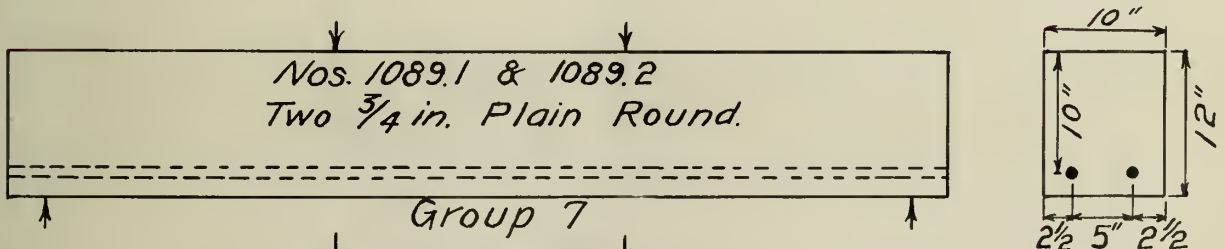


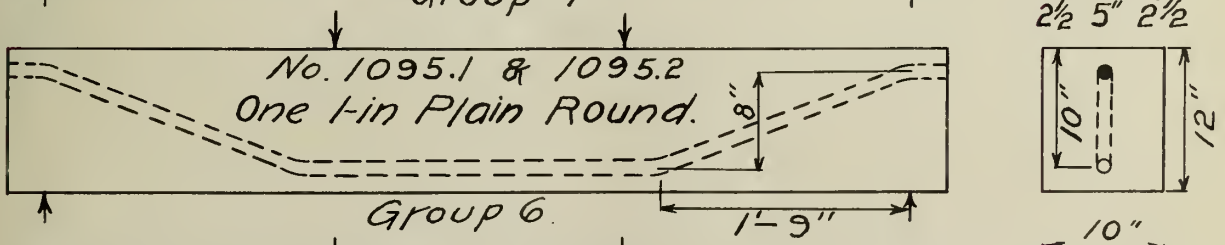
(d) Group 4.

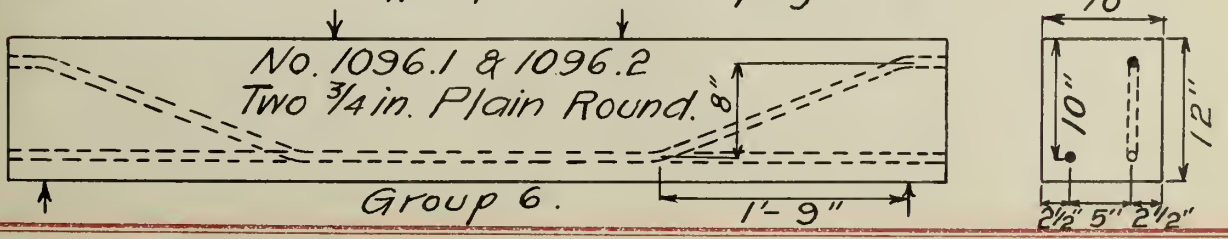

2'-0"
Nos. 1086.1 & 1086.2
One 1in Plain Round
r= 2"
4"
3"
6'-0"
3"
Group 5.
10"
10"
12"

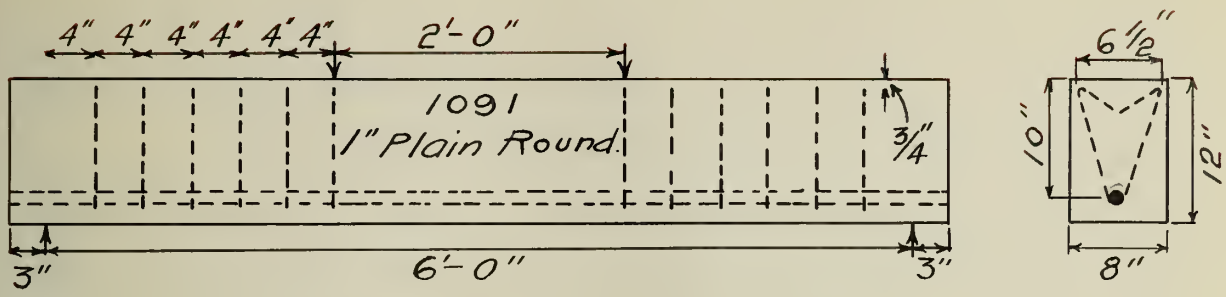

Nos. 1087.1 & 1087.2
One 1in Plain Round.
r=2"
8"
Group 6.
1'-0"
10"
10"
12"


Nos. 1088.1 & 1088.2
Two 3/4 in. Plain Round.
r=2"
8"
Group 6
1'-0"
10"
10"
12"
2½" 5" 2½"

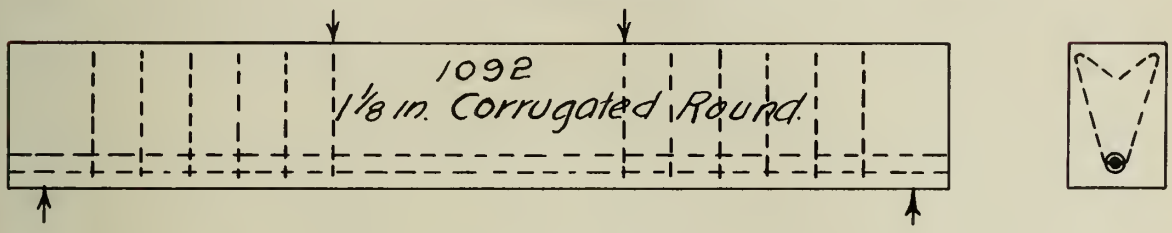

Nos. 1089.1 & 1089.2
Two 3/4 in. Plain Round.
Group 7
10"
10"
12"
2½ 5" 2½

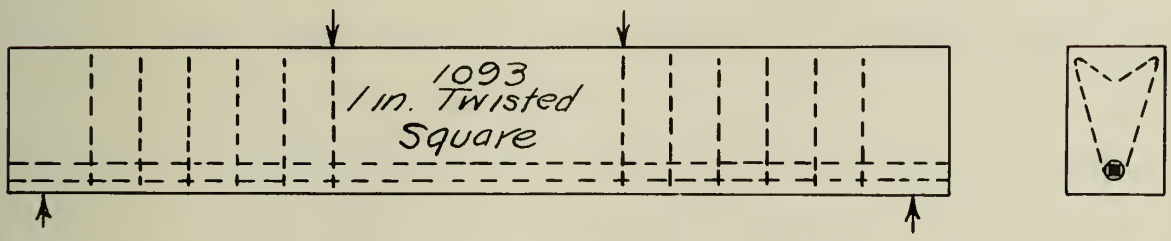

No. 1095.1 & 1095.2
One 1-in Plain Round.
8"
Group 6.
1'-9"
10"
12"

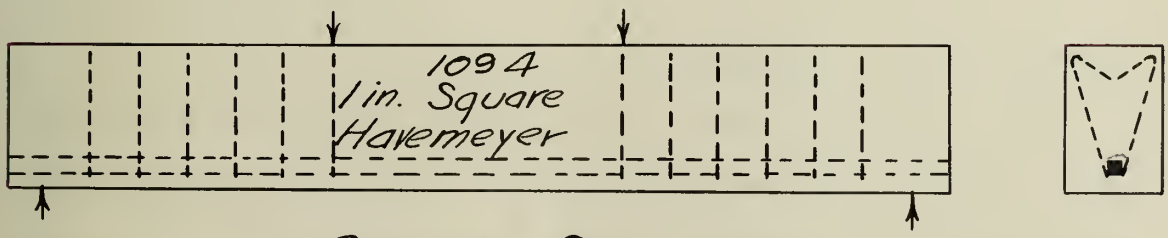

No. 1096.1 & 1096.2
Two 3/4 in. Plain Round.
8"
Group 6.
1'-9"
10"
10"
12"
2½" 5" 2½"



Stirrups 1/4 in. Plain Round Bars.







Group 8.

made from each wheelbarrow load.

The pull-out specimens were stored under the same conditions as the beams. The forms were removed in four days, and the specimens were placed under the burlap with the beams.

(b) Concrete Cylinders:- Two cylinders were made for compression tests from each batch, one cylinder being made from the first wheelbarrow load of concrete and the other from the third or last wheelbarrow load. The cylinders were made in metal forms resting on oiled glass plates. The concrete was deposited in 3 inch layers and tamped lightly. When the form was filled it was allowed to stand for two or three hours, when a neat cement mortar was placed on the upper surface and an oiled glass plate was pressed down firmly to insure a smooth surface. The forms were removed in four days, and the specimens stored in damp sand. All auxiliary specimens were removed to the testing laboratory one week before being tested and allowed to dry out.

(c) Control Beams and Cubes:- The control beams were made in wooden forms and the cubes in metal forms. Beams No. SC1, SC4, and SC7 are the only ones having cubes or control beams as auxiliary pieces. These specimens were made with the same care and stored under the same conditions as the beams.

15. Testing Apparatus:- The various tests on beams and auxiliary specimens were made in 200,000 lb. Olsen beam testing machine, Figure 10 ; a 100,000 lb. long screw Riehle machine, Figure 6 ; a 100,000 lb. Riehle tension machine,

Figure 6 ; a 100,000 lb. Philadelphia machine, Figure 11 ; and two dynamometer machines devised for the long time tests, see Figure 15 .

The two dynamometer machines are shown in Figure 15 These machines were devised for long time tests. A large steel H-section beam was placed upon wooden blocks on the floor of the laboratory and the apparatus built upon this H-beam. The support of one end of the beam under test consisted of steel plates, a heavy car spring, and a steel roller and bearing block. A screw jack formed the other support. By screwing up the jack, tension was thrown into two vertical steel rods and the load was applied to the beam through these rods. The car spring serves to maintain a constant load. The spring was calibrated for load-compression so that the concrete beam would be horizontal when the final load was reached. The applied load on the beam was measured by a calibrated spring dynamometer consisting of nickel steel plates and an Ames dial. The load as obtained by this instrument is not in error more than 150 lbs. at the most. Calibration graphs for the two spring dynamometers are shown in Figures 27 and 28 .

Ames dials were used to measure the center deflection of all concrete beams, and the slip of the ends of the reinforcing bars. A movable plunger transmits its motion to a hand on the face of the dial. The dial face is graduated into 100 divisions, each division representing 0.001 inch movement of the plunger, and by estimating to tenths of a division a movement

of 0.0001 inch may be read.

16. Preparation and Testing of Reinforced Concrete Beams:- One side of the beam was whitewashed with plaster of paris in order to make the cracks more easily discernible. The center line of the load points and the supports were laid off and marked on the whitewashed face. In the long time tests, one end of the beam was supported by a heavy car spring, and the other by a solid support as shown in Figure 10 . This car spring held the load constant throughout the test. The beams which were loaded progressively to failure, were supported on solid rocker bearings. The load was transmitted to the concrete by means of a steel bearing plate. A cushion of rubber fire hose or a bed of plaster of paris mortar was placed between the bearing plate and the beam to insure an even distribution of the pressure. The loads were concentrated at the center of the bearing plates by means of 2-inch steel rollers. A short I-beam or steel plate served to transmit the load from the head of the testing machine to the third points of the beam. The load applying apparatus was carefully centered to insure an equal distribution of the load.

The deflection of the beam at the center was measured by an Ames dial fastened to a wooden bar. This bar had a bearing on the concrete at two steel points over the center of the supports and was clamped to the beam at these points. The movement of the beam was transmitted to the plunger of the dial by means of a metallic strip fastened to the concrete by

plaster of paris. This deflection apparatus gave accurate measurements in the tests in which the beams were loaded quickly to failure, but the apparatus is not very reliable in long time tests, due possibly to the effect of the weather conditions on the wooden bar.

The slip of the ends of the reinforcing bars was measured by Ames dials fastened to wooden or metal yokes securely clamped to the ends of the beam.

Four men were required to make a test; one to operate the machine, one at each end of the beam to read the Ames dials, and one at the center to observe the deflection and to do the necessary recording. The load was applied in 2000 lb. increments. The machine was stopped after each 2000 lb. increase in load, and the cracks marked on the whitewashed face of the beam and general notes taken. At first both faces of the beam were whitewashed, but it was found that the cracks appeared in the same position on the opposite faces, after which only one face was whitewashed. The long time test beams were loaded in 2000 lb. increments until the desired load was reached. The beams were then left under this load until failure occurred or until it was necessary to remove them from the machine to make way for other tests. The rate of application of the load was about 0.05 inches per minute.

17.. Pull-out Tests:- The pull-out tests were made in a 100,000 lb. Riehle machine. Figure 6 shows a specimen set up in the machine ready for testing. The reinforcing bar pro-

jects through a central hole in a spherical bearing block and is caught by the grips in the movable head of the testing machine. Two steel plates separated by a rubber gasket are placed between the spherical block and the concrete. The purpose of the rubber gasket is to decrease the rate of application of the load when first applied, and to minimize the effect of any jar or shock that might result from the slipping of the grips on the reinforcing bar. The slip of the end of the bar as it was pulled out of the concrete block was measured by means of an Ames dial fastened to a wooden yoke, which was securely clamped to the concrete block. Two men were required to make a pull-out test, one to operate the machine and the other to observe and record. The rate of application of the load was about 0.05 inch per minute.

18. Cylinder and Auxiliary Specimen Tests:- The cylinders were tested in the 100,000 lb. Riehle and the 200,000 lb. Olsen machines. A bed of plaster of paris mortar was placed upon an oiled glass plate, and the cylinder set firmly into this bed of mortar. The top face of the cylinder was prepared in the same manner. When the mortar had set, the glass plates were removed leaving a thin smooth bearing surface. Planed cast iron plates were placed on each end of the cylinder when set up in the testing machine and a spherical bearing block placed between the top plate and the moving head of the testing machine. In one half of the cylinder tests, extensometer readings were taken to determine the relation between stress and deformation

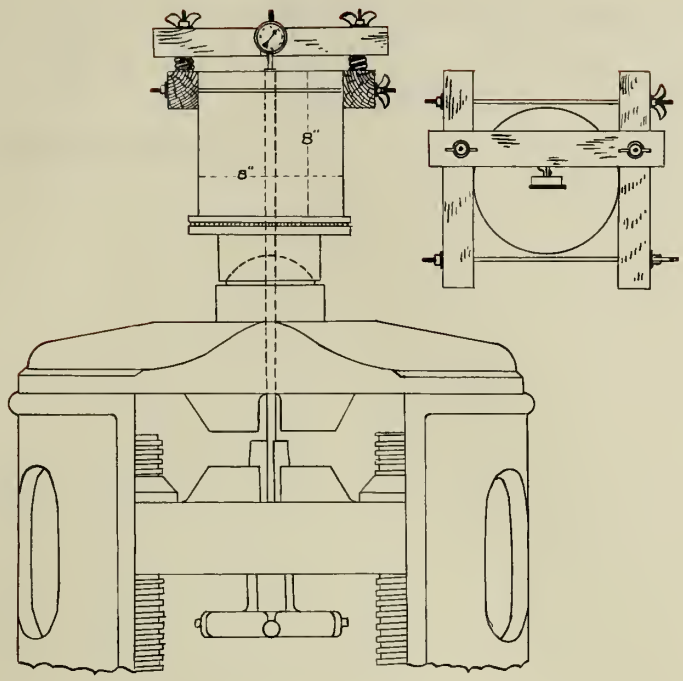


Figure 6.

Pull-out Specimen in Machine Ready for Test.

and to obtain the modulus of elasticity of the concrete in compression. The extensometer was devised by the men on the Engineering Experiment Station Staff, and has been used for some time on cylinder tests. The deformation readings were obtained by means of a Wissler dial.

The control beams were tested on a 3-foot span and were prepared for testing in the same manner as the reinforced beams. No data were taken except the load at rupture, from which the modulus of rupture was obtained.

The 6-inch cubes were set up in plaster of paris mortar and tested in the same manner as the cylinders except that no deformations were measured.

All the apparatus used in these tests and described

above has been well tried out in previous tests conducted by the Engineering Experiment Station and has been found to give accurate and reliable data.

IV.

EXPERIMENTAL DATA AND DISCUSSION.

IV.

EXPERIMENTAL DATA AND DISCUSSION.

19. Explanation of Diagrams, Tables, and Figures:- A brief explanation of the diagrams, tables, and figures, will be given, as the most important features of the test data are contained in them. Many of the diagrams, tables, and figures are easily understood upon inspection, and require no further explanation.

Table 9 is a condensed summary of the test data for the beams and auxiliary specimens, with the exception of the tests of the control beams and 6-inch cubes, the results of which are given in Table 7 . In the column giving the compressive strength of the concrete cylinders, each value is an average of two tests unless marked with an x, in which case the given value is for one test only. The values for the bond resistance given for the pull-out tests are the average of three tests unless marked ② or ①, the figure in the circle referring to the number of tests of which the given value is an average. In the beam test data, the values for the loads are the applied loads as read from the scale beam of the testing machine, and the weight of the beam and loading apparatus is not included. The column designated as "Dead Load on Beam" gives the sum of the weights of the beam and loading apparatus. This dead load was added to the given applied load in calculat-

ing all unit stresses. The weight of the 10 x 12 inch beams is taken as 800 lb., and that for the 8 x 12 inch beams as 650 lb. The loading apparatus on the beams tested in the Riehle and Olsen machines weighed 100 lb., in the Philadelphia machine 150 lb., and in the Dynamometer machine 480 lb. The tensile stress in the steel was calculated from the formula

$$f_s = \frac{M}{A(d-z)}$$

Where $z = 1/3\ kd\ (1 + 1/4\ \frac{q}{3-q})$

and $k = \sqrt{\frac{2\ pn}{1 - 1/3q} + \frac{p^2n^2}{(1-1/3q)^2}} - \frac{pn}{1-1/3q}$

The value of q was determined from the formula

$$\frac{f_c}{f_c'} = (1 - \tfrac{1}{2}q)\ 2q$$

For a derivation of the above formulas see Bulletin 4 of the Engineering Experiment Station. Table 8 shows the values of A, z, k, q, f_c, and n, which were used in the calculation of f_s for each beam. The value of f_c was taken as the average ultimate compressive strength of the auxiliary cylinders. The values of the vertical shearing stress and computed bond stress were calculated by the formulas $v = \frac{V}{bd'}$ and $u = \frac{V}{mod'}$, respectively.

Figures 16 to 26 inclusive show views of the tested beams. At the right end, the number of the beam and the applied load are given (dead load not included.). When the load is not designated as maximum load, the beam was not tested to failure. The arrow heads indicate the position of the load points and the supports. The letters N, E, and S at the left

end refer to the north, east, and south ends of the beam respectively, as it was placed in the testing machine. When not lettered, the left end is the north end. The irregular black lines are the cracks in the concrete. These cracks were painted so that they would show up clearly in the photograph. The cracks were carefully marked for each 2,000 lb. increment in load, and the figure at any point indicates the load in thousands of pounds when the crack had opened up to that point. The lowest figure at any crack is the applied load when the crack was first visible.

Figures 27 and 28 show calibration-graphs for the two Spring Dynamometers used to measure the applied load in the testing machines shown in Figure 15 . The Dynamometers were calibrated in a 100,000 lb. Riehle machine, using the same steel bearing plates as were used when the beams were tested. The ordinate gives the applied load for any given deflection plotted as abscissae, as read from the Ames dial.

Figures 29 to 32 inclusive show the variation in the daily temperature and hygrometer readings taken in the laboratory where the test specimens were stored. The upper curve gives the daily variation in the percentage of moisture in the air in the storage room, and the lower curve the daily variation in temperature. Readings were taken at 7 A. M. and 5 P. M. daily except Sunday, when one reading at noon was taken.

Figures 33 to 35 inclusive show the relation between unit compressive stress and unit deformation for the concrete cylinders. The deformations were measured over a

10-inch gage length. The number on each diagram is the number of the beam which was made from the same batch of concrete. The straight line is the initial rate of deformation of the cylinder and the tangent of the angle which this line makes with the horizontal is the value of the initial modulus of elasticity of the concrete.

Figures 36 to 43 inclusive show the relation between unit bond stress and end slip for the pull-out tests. Starting with zero stress and zero slip, each diagram continues vertically upward to the first circle which is the value of bond stress when slipping began. The concrete in the pull-out specimens came from the same batch of concrete as the beams having the same number.

Figures 45 to 59 inclusive show load-deflection and load-end slip diagrams for the concrete beams. The slip of the reinforcing bar at the end of the beam where failure occurred is plotted to the same scale as the deflection in order to show the relation between end slip and deflection. The first circle on the ordinate through zero gives the load at which the end slip began.

Figures 60 to 96 inclusive show load-end slip diagrams for both ends of the concrete beams, the slip at each end being plotted in the direction in which it took place, that is toward the center of the beam. A sketch of the beam and disposition of the reinforcement is shown at the top of each sheet. The exact location and extent of the cracks for each 2,000 lb.

increment in load has been transferred from the photographs to the sketch to enable one to see the relation between the cracks and end slip. Upon examination of the end slip diagrams and the cracks, it is generally possible to tell whether the primary cause of failure was due to bond or diagonal tension.

Figures 97 to 107 show the increase in deflection and end slip with time for the beams which were kept under a continued load. In the upper part of the diagram is shown the increase in deflection with time. Upon inspection of these diagrams, it is seen that on a certain day the deflection is frequently less than it was on the previous day, but considering the diagram as a whole there is a general upward trend. This decrease in the value of the deflection is probably due to the effect of the moisture in the air upon the wooden bar used in the deflection apparatus, since it is likely that the beam would not straighten up under a constant load. In some of the diagrams, it was not possible to plot all of the observed data to the desired scale continuously one one page, and in this case the graph is doubled back upon itself.

20. Phenomena of Tests:- The beams are divided into eight groups, each group being planned to bring out some particular phase of bond action. Each individual beam test will be taken up and the phenomena described in detail.

Group 1.

Effect of a Continued Load upon the Action of the Deformed Bar as Contrasted with the Plain Bar:- The beams in Group 1, No. 1 to 8 inclusive, were 8 x 12 inches in section

and reinforced with a single longitudinal bar placed 10 inches below the top of the beam. Four kinds of bars were used, plain round, corrugated round, Havemeyer square, and twisted square. Figure 9 is a photograph of a short length of each type of bar. Figure 5 shows the details of the beams. At first, it was the intention to apply load to these beams until an end slip of 0.001 inches was obtained, and then leave the beam under this load until failure occurred. After the first two beams were tested, it was seen that an end slip of 0.001 inch was too large, and in the remaining tests a smaller value was chosen. These beams were removed from under the wet burlap when 60 days old and stacked in tiers in the laboratory until tested. No auxiliary specimens were made with these beams. All stresses given in the following descriptions of the beam tests are expressed in lbs. per sq. inch.

Beam No. 1. This beam was tested at an age of 182 days, and was reinforced with one 1 1/16 inch plain round bar. At 4000 lb. load, the beam began to deflect more rapidly, but the first tension crack was not visible until the load reached 8000 lb. At 13,350 lb. the north end of the reinforcing bar began slipping. At this load $u = 241$ lb. per sq. inch, $v = 101$ lb. per sq. inch. At 15,700 lb. the bar began to slip at the south end. No diagonal tension cracks were visible at this stage of the test. At 20,000 lb. the bar had slipped 0.001 inch at the north end and 0.0002 inch at the south end. The beam failed very suddenly after this load had been maintained for

about one minute. Maximum load 20,000 lb., u = 356 v = 148. Figure 16 shows a view of the beam after failure, Figure 45 shows the load-deflection diagram, Figure 45 the load-end slip diagram, and Figure 10 a photograph of the beam in the testing machine after failure.

Beam No. 2:- This beam is a companion beam of No. 1, and was tested at an age of 233 days in the dynamometer machine Figure 14 . Three cracks were visible at 6000 lb. At 11,000 lb. the bar began to slip at the east end, u= 207, v = 86. At this stage of the test, there was one crack in the east third of the beam, but this crack had not extended quite to the center of the beam. At 16,000 the bar began slipping at the west end. At 17,000 lb. the east end slip was 0.0003 inch and the west end slip was 0.0001 inch. At 17,000 lb. u = 304, v = 127. The beam was left under this load for 33 days, at which time the east end slip had increased to 0.0024 inch, and the west end slip to 0.0008 inch. At this time the load was removed to make way for another test. The east end slip recovered to 0.002 inch, the west end slip recovered to 0.0007 inch, and the permanent set in deflection at the center of the beam was 0.041 inch, when the load was removed. The beam was set aside in the laboratory for 38 days when the load of 17,000 lb. was reapplied. The dials were left on the beam for several hours after the load was removed, and as no further recovery of end slip occurred, it was assumed that no recovery of end slip took place during this period of rest. When the load was reapplied, the end slip

Beam No. 3.- This beam was reinforced with one 1 1/8 in. corrugated round bar, and was tested at an age of 186 days. At 8,000 lb. the first cracks appeared. At 14,350 lb. the south end of the bar began slipping, u = 245, v = 108. At 24,000 lb., the south end slip was 0.0003 in. and the north end began to slip, u = 402, v = 177. At the beginning of the test, it was the intention to load the beam until an end slip os 0.001 in. was obtained, but at 24,000 lb. and an end slip of 0.0003 in. the diagonal cracks had opened up considerably and the beam was left under this load. The beam held this load for 30 minutes when it failed suddenly. The south end slip just before failure was 0.003 in. and the north end slip 0.0001 in. After the beam failed, the north end slip was 0.005 in. Fig. 11 shows the beam in the testing machine after failure. Fig. 16 shows a view of the beam after failure. Fig. 62 shows the load-end slip diagram and Fig. 46 shows the load-deflection diagram.

at the east end increased to 0.0034 inch and the west end slip to 0.0009 inch. The center deflection was 0.107 inch just before the load was taken off on the thirty-third day, and this value increased to 0.128 inch when the load was reapplied. The beam failed during the night after it had held up under the applied load of 17,000 lb. for 65 days. On the sixty-fifth day the east end slip had increased to 0.0165 inch, the west end slip to 0.0015 inch, and the center deflection to 0.147 inch. The beam failed by breaking across its entire depth along a plane extending downward at an angle of 45° from the east load point. (Figure 61). The bar slipped about 5/8 inch at the east end.

On the thirteenth day after the load was first applied, the sum of the north and south end slips was 0.0025 inch, and there were five cracks in the beam. The sum of the widths of these cracks at a plane through the center of the reinforcing bar was 0.033 inch, which value is 0.03 inch greater than the sum of the end slips.

Beam No. 4:- This beam is a companion beam of No. 3, and was tested at the age of 236 days. At 6000 lb., the first cracks appeared. At 13000 lb. u = 224, v = 99, the north end of the bar began to slip. At 17,000 lb. the south end began to slip, and the north end had slipped 0.0003 inch. At 18,000 lb., u = 304, v = 134, the north end slip was 0.0003 inch, and the south end slip was 0.0001 inch. The beam was left under

this load for 28 days, during which time the north end slip increased to 0.0004 inch and the south end to 0.0003 inch. On the twenty-eighth day, the load was released and the end slip recovery was 0.0001 inch at each end. The beam had a permanent set of 0.061 inch in the deflection at the center. The beam was set aside in the laboratory for 39 days to make way for another test. When the beam was put back in the machine and the load reapplied, the north end slip increased to 0.0005 inch and the south end to 0.0003 inch, the same value before the load was released. The center deflection was 0.121 inch before the load was released and 0.145 inch when reapplied. At the time of writing this thesis, the beam had been holding the load for a total of 55 days. After the load was reapplied on the twenty-eighth day, there was no further increase in the end slip nor any indication of immediate failure on the fifty-fifth day. Figure 17 shows a photograph of this beam after it had held the continued load for 28 days, Figure 46 shows the load deflection diagram, Figure 63 shows the load end-slip diagram, and Figure 98 shows the time-deflection and the time-slip diagram for this beam.

Beam No. 5:- This beam was reinforced with one 1-inch square Havemeyer bar and was tested at an age of 188 days. At 8,000 lb, cracks were visible. At 15,750 lb., both ends of the bar began to slip, u = 236, v = 118. At this load there was a crack outside each load point extending a little above the center

of the beam. At 16000 lb. both ends of the bar had slipped 0.0001 inch, u = 239, v = 120. The beam was left under this load. In six hours the south end slip increased to 0.0009 inch and the north end slip to 0.0004 inch. On the fifty-ninth day the south end slip had increased to 0.00075 inch, the north end slip to 0.003 inch, and the center deflection had increased 0.059 inch. On the fifty-ninth day the load was increased to 18000 lb., u = 268, v = 134. The beam failed during the night of the sixty-seventh day. On the sixty-seventh day, just before failure occurred, the south end slip was 0.022 inch, the north end slip 0.0056, and the center deflection was 0.114 inch. On the fifty-seventh day, the sum of the two end slips was 0.0102 inch, and the sum of the widths of all the cracks in the beam along a plane through the center of the reinforcing bar was 0.049 inch, which value is 0.039 inch greater than the sum of the end slips. In beam No. 2 the sum of the end slips was 0.03 inch less than the sum of the widths of the cracks. Figure 12 shows a view of the crack at which failure occurred in beam No. 5. This photograph was taken when the beam had been under load 57 days, and the width of the crack along the line ac, which is the center of the reinforcing bar, is 0.016 inch. Figure 13 is a view of the same crack after the beam had failed. Notice that in Figure 12 there is no evidence of the splitting of the concrete along the plane of the reinforcing bar as is seen in Figure 13 which is a photograph taken after failure Figure 18 is a view of the beam after failure. Figure 47 shows

the load-deflection diagram, Figure 64 shows the load-end slip diagram, and Figure 99 shows the time-deflection and time-slip diagrams for this beam.

Beam No. 6:- This beam is a companion beam of No. 5 and was tested at an age of 250 days. At 6,000 lb. a crack was visible. At 8,000 lb. u = 125, v = 62, south end of the bar began to slip. At 9420 lb., the north end began to slip. At 20,000 lb. u = 296, v = 148, the north end slip was 0.0002 inch, south end slip 0.0002 inch, and center deflection 0.087 in. The beam was left under this load for 10 days, when it was taken out of the machine and set aside for 25 days. When the load was released, the north end slip recovered 0.0002 inch, the south end slip 0.0001 inch, and the permanent set was 0.048 inch. When the load was reapplied the north end slip increased to 0.0009 inch, south end slip to 0.0008 inch, and center deflection to 0.126 inch. At the time of writing this thesis, the beam had been under load for 55 days and there was no indication of immediate failure. On the fifty-fifth day the north end slip was 0.0021 inch, south end 0.0054 inch, and center deflection 0.158 inch. End slip occurred at a comparatively low bond stress in this beam, but the bar slipped at a slow rate after once starting. Figure 18 shows a view of the beam after it had been under load 10 days, Figure 47 shows the load-deflection diagram, Figure 65 shows the load-end slip diagram, and Figure 100 the time-slip and time deflection diagrams.

Beam No. 7:- This beam was reinforced with one 1-inch twisted square bar and was tested at an age of 188 days. At 8,000 lb. four cracks were visible. At 10,000 lb., u = 154, v = 77, the north end began slipping. No diagonal cracks were visible at this load. At 16,000 lb., the south end began slipping. At 20,000 lb., u = 296, v = 148, the north end slip was 0.0003 inch, the south end 0.0002, and the center deflection 0.074 inch. The beam was left under this load for 59 days, at the end of which time there was no indication of immediate failure. On the fifty-ninth day the north end slip was 0.0025 inch, south end slip 0.0007 inch, and center deflection 0.156 inch. The beam was set aside on the fifty-ninth day and never put under load again. When the load was released, the north end slip recovered 0.0002 inch, the south end 0.0002 inch, and the permanent set at the center was .094 inch. The dials were left on the beam for four hours after the load was released and there was no further recovery in end slip or deflection during this time. Figure 18 shows a photograph of the beam, Figure 47 shows the load-deflection diagram, Figure 66 the load-end slip diagram, and Figure 101 the time-deflection and time-slip diagrams.

Beam No. 8:- This beam was similiar to No. 7 and was tested at an age of 189 days. Cracks were visible at 8000 lb. At 14600 lb., u = 219, v = 110, the north end began to slip. No diagonal cracks were visible at this load. At 19800 lb., the south end began slipping. At 20,000 lb., u = 296, v = 148,

the north end slip was 0.0003 inch, the south end 0.0001 inch, and the center deflection 0.078 inch. The beam was left under this load, and failure occurred during the night of the thirty-fifth day. On the thirty-fifth day the north end slip had increased to 0.0061 inch, the south end to 0.0006 inch, and the center deflection to 0.129 inch. The concrete at the north end where failure occurred was broken into fragments. Several pieces of the stone failed in tension. From the crack which caused failure to the end of the beam, the concrete was split away from the reinforcing bar. Several small air voids were visible on the fractured surfaces. Figure 16 shows a view of the beam taken after failure, Figure 67 the load-end slip diagram, Figure 47 the load-deflection diagram, and Figure 102 the time-slip and time-deflection diagrams.

Group 2.

Action of Plain Round Rods: 60-Day Concrete:- This group contained three beams reinforced with a single plain round bar 1 inch in diameter. Load-deflection, load-end slip, time-deflection, and time-slip diagrams are shown in Part V. Figure 19 shows a view of the beams after failure. The formula for bond stress does not take into account the bond on the bars from the center of the supports to the ends of the beams. For that reason, this part of the bar was wrapped with oiled paper in all of the beams tested except the three in this group.

Table 7 gives the results of tests on the control beams and 6-inch cubes made from the same concrete as these beams.

Beam No. SC1:- At 4,000 lb. the first tension crack was visible. At 6,000 lb., three more cracks opened up. At 9,000 lb., u = 178, v = 70, slip began at the north end. At 11,000 lb., the south end began to slip. The north end began to slip first but failure occurred at the south end. At 14,000 lb., u = 270, v = 106, the north end slip was 0.0004 inch, and the south end slip 0.0015 inch. At this load, the south end of the bar began to slip without any increase in load and when the slip was 0.016 inch, the beam suddenly failed. The beam was holding 13,900 lb., when the sudden failure occurred. The three beams in this group were tested with a car spring under the north end, and due to the stored energy in the spring, the beams failed with considerable violence.

Beam No. SC4:- At 4,000 lb. tension cracks were visible. At 14,000 lb., u = 270, v = 106, end slip began at both ends of the beam simultaneously. This is the load which caused failure in No. SC1. At this load a crack outside each load point had extended well up into the upper half of the beam and was turning in diagonally toward the load point. At 17,260 lb., u = 328, v = 129, the maximum load was reached, and the south end slip increased without any additional load. At this load, the north end slip was 0.0004 inch, and the south end slip was 0.0012 inch. The south end slip gradually increased until it reached a value of 0.01 inch, when the beam failed with considerable force. From the left support to the crack causing failure, the concrete split off below the reinforcing bar.

Several of the pieces of stone were broken in two. The bar was well coated with rust.

Beam No. SC7:- A tension crack was visible at 4,000 lb., and four more cracks had opened up at 6,000 lb. At 11,000 lb., u = 215, v = 84, the south end slip began. At 13,000 lb. the north end slip began. At 14,000 lb., u = 270, v = 106, the north end slip was 0.0001 inch, and the south end slip was 0.0002 inch. When the ends of the bar began slipping, the cracks outside the load points turned diagonally toward the load points. The load-deflection diagram, Figure 48 shows that this beam deflected more rapidly than the other two. The beam was then left under 14,000 lb. load, with an end slip of 0.0002 inch at the south end. In six hours, the end slip had increased to 0.0014 inch. The beam held this load for 119 hours, when it failed suddenly. Just before failure occurred, the south end slip was 0.0045 inch, and the north end slip 0.0012 inch. At failure the concrete below the reinforcing bar, from the right support to the crack causing failure was broken off. Several pieces of the stone were broken in tension. The bar was well coated with rust.

Group 8.

Bond Action in Beams with Loose Vertical Stirrups:- The tests of the beams in Group 8, No. 1091 to 1094 inclusive, will be described at this point, as these tests were made as a supplementary series to the time tests. These beams were simiiliar to those in Group 1 in fabrication, with the exception that

they were reinforced with loose vertical stirrups of 1/4-inch plain round, mild steel bars placed 4 inches apart in the outer thirds of the beam. The stirrups were wound with one complete turn around the longitudinal bar and extended upward and outward to a point 3/4-inch from the top face and 3/4-inch from the side face of the beam, and from this point were bent unward toward the center of the beam. A direct bearing of the stirrup against the longitudinal bar was insured by the wrapping of the stirrup around the bar.

The beams were tested at approximately the same age. A car spring formed the support at one end of each beam in order to maintain a constant load during the test. The beams were loaded until practically the same bond stress existed in all the beams. This load was increased 500 lb. each day until failure occurred. Up until the time the first beam failed, the bond stress was practically the same amount in all the beams throughout the test. Figure 26 shows a view of the beams after failure. Figure 57 shows the load-deflection diagrams, and Figure 60-96 shows the load-end slip diagrams for the loads which were applied on the first day of the test. Figures 104 to 107 inclusive show the increase in deflection and end slip with time and increasing load.

Beam No. 1091:- This beam was reinforced longitudinally with one 1-inch plain round bar. At 6,000 lb., three tension cracks were visible. At 9,500 lb., u = 187, v = 74, the south end of the bar began to slip, and when this load had been maintained for a few minutes, the north end began to slip. The beam

was then left under this load for 24 hours, when the load was increased 500 lb. every day until failure. The beam failed during the night after the ninth day at an applied load of 14,000 lb., u = 270, v = 106. On the ninth day, the north end slip was 0.001 inch. The south end slip was the greater until the sixth day, when the north end of the bar began to slip more rapidly and failure occurred at this end of the beam.

Beam No. 1092:- This beam was reinforced longitudinally with one 1 1/8-in. corrugated round bar. At 6,000 lb., three tension cracks were visible. At 10,500 lb. u = 188, v = 83, both ends of the bar began to slip but neither end slipped more than 0.0001 inch, until the sixth day, when the applied load was 13,500 lb. On the twenty-first day, the west end slip was 0.0017 inch, and the east end slip was 0.0005 in. On the twenty-second day the west end slip had increased to 0.026 in., and the east end slip was 0.0007 in. The load had fallen off about 400 lb. When the load was increased to 21,500 lb., u = 366, v = 161, the beam failed very slowly due to the action of the stirrups in preventing a sudden diagonal tension failure as was the case in the beams without web reinforcement.

Beam No. 1093:- This beam was reinforced longitudinally with one 1-in. twisted square bar. At 6,000 lb., three tension cracks were visible. At 12,000 lb., u = 187, v = 94, both ends of the bar began to slip. The beam was left under this load until the next day when the load was increased 500 lb. each day until failure occurred. The beam failed very slowly on the thirteenth day after the load was increased to 18,500 lb., u = 281, v = 140.

Beam No. 1094:- This beam was reinforced longitudinally with one 1-inch square Havemeyer bar. Three tension cracks were visible at 6,000 lb. At 10,000 lb., u = 154, v = 77, both ends of the reinforcing bar began to slip. At 12,000 lb., both ends of the bar had slipped 0.0001 inch. The beam was then left under this load until the following day when the load was increased 500 lb. each day until the beam failed. The beam failed during the night after the twelfth day, when the load was 18,000 lb., u = 278, v = 134. On the twelfth day, the south end slip was 0.006 inch and the north end slip was 0.0015 inch. The beam failed at the north end, and the bar pulled out of the concrete about 1/2 inch at this end.

Group 3.

Effect of Settlement of Concrete from Restrained Bar, and Difference in Pressure Between Top and Bottom of Beam:- The beams in this group, No. 1081.1 to 1084.2 inclusive, were made 10 inches wide in order to reduce the shearing stresses and thereby prevent diagonal tension from playing such an important part in the failure of the beams as was the case in the 8 x 12 beams. The beams were made upside down with the reinforcing bar placed 2 inches from the top of the beam. When tested, the beams were turned over into their natural position with the tension side down. Both plain round and corrugated round bars were used. Three beams were reinforced with a plain round bar which was allowed to settle with the concrete when setting, and two beams were made in which the plain round bar was held up by

wires and the concrete allowed to settle away from the bar. Four beams were made with corrugated round bars, the bars being allowed to settle in two of the beams and restrained in the other two.

This series of tests to determine the effect of settlement of the concrete away from the under side of restrained reinforcing bars was suggested by the settlement found in continuous beams as described in a thesis written in 1913 by Mr. H. F. Gonnerman. In the tests made by him settlement cracks as much a 0.1 inch in width were found under the reinforcing bars which were bent up to take negative bending moments over the supports of the continuous beams. Another similiar and common example where settlement is likely to occur is in a continuous floor slab where the bars are bent up to take negative bending moment over the columns.

Figures 16 to 26 inclusive show views of these beams after failure. Figures 45 to 59 inclusive show the load-deflection diagrams and Figures 60 to 96 inclusive show the load-end slip diagrams.

Beam No. 1081.1:- This beam was reinforced with one 1-inch plain round bar which was allowed to settle with the concrete. At 8,000 lb., two tension cracks opened up to the center of the beam. At 10,000 lb., u = 198, v = 62, the bar began to slip at the north end. At 12,000 lb., the south end of the bar began to slip. At maximum load 16,400 lb., u = 315, v = 99, the end slip was 0.048 inch at the north end and 0.0001

inch at the south end.

Beam No. 1081.2:- This beam was reinforced with one 1-inch plain round bar which was allowed to settle with the concrete. At 8,000 lb., one tension crack was visible near the center of the beam. At 10,000 lb., u = 198, v = 62, the north end of the bar began to slip. At 12,000 lb., the south end slipped a very slight amount, and the north end slip was 0.0008 inch. At this load u = 235, v = 74, the beam failed suddenly at a crack just outside the north load point. This crack had not opened before the load of 12,000 was reached.

Beam No. 1081.3:- This beam was reinforced with one 1-inch plain round bar which was allowed to settle with the concrete. At 10,000 lb., u = 198, v = 62, both ends of the bar began to slip. At 18,000 lb. a new crack opened up close to the existing crack under the north load point, and at failure this crack opened about 3/16 of an inch. The beam failed at 18,300 lb., u = 350, v = 110. At this load the north end slip was 0.032 inch, and the south end slip was 0.0061 inch.

Beam No. 1082.1:- This beam was reinforced with one 1-inch plain round bar which was restrained by wires and prevented from settling. At 8,000 lb., a tension crack extended to the center of the beam. At 10,000 lb., u = 198, v = 62, the north end of the bar began to slip. The machine was stopped at this load to mark up the cracks. While this was being done the load fell off 100 lb., but there was no increase in slip. When the machine was started the beam failed suddenly as if it were a

plain beam, just as the load reached 10,000 lb. the second time. The north end slip was 0.047 inch after failure, and this slip took place almost instantaneously. The dial at the south end of the beam indicated a very slight slip after failure.

Beam No. 1082.2:- This beam was reinforced with one 1-inch plain round bar which was prevented from settling with the concrete. At 8,000 lb., one tension crack extended to the middle of the beam. At 12,000 lb., u = 235, v = 74, both ends of the bar began to slip. The beam failed in bond at the south end at a load of 17,650 lb., u = 338, v = 106. At this load the north end slip was 0.0068 inch. This beam was much stronger than its companion beam No. 1082,1.

Beam No. 1083.1:- This beam was reinforced with one 1 1/8-inch corrugated round bar which was free to settle with the concrete. At 10,000 lb., u = 176, v = 62, both ends of the bar began to slip. There were no visible cracks in the outer thirds of the beam at this load. The end slip began at a comparatively low bond stress in this beam, but this slip did not reach 0.0003 inch until 18,000 lb. was reached. At 23,640 lb., diagonal tension cracks appeared and the beam failed at the south end. At this load, u = 397, v = 140, the south end slip was 0.013 inch, and the north end slip was 0.0089 inch.

Beam No. 1083.2:- This beam was reinforced with one 1 1/8-inch corrugated round bar which was free to settle with the concrete. At 12,000 lb., u = 209, v = 74, the north end of the bar began to slip. At 14,000 lb., the south end of the bar began to slip and the north end slip was 0.0001 inch. At 24,000 lb.,

a diagonal crack opened up outside the north load point and the north end of the bar began to slip at a rapid rate. At 24,000 lb., u = 410, v = 145, the beam failed. At this load the north end slip was 0.0068 inch, and the south end slip was 0.0007 inch.

Beam No. 1084.1:- This beam was reinforced with one 1 1/8-inch corrugated round bar which was prevented from settling with the concrete. At 14,000 lb., u = 241, v = 85, both ends of the bar began to slip. The maximum load was reached at 16,000 lb., u = 272, v = 97. At this load, the north end slip was 0.0002 inch, and the south end slip was 0.0002 inch. The beam failed more slowly than the beams with plain round bars which were prevented from settling. The beam failed in bond at the south end followed by diagonal tension.

Beam No. 1084.2:- This beam was reinforced with one 1 1/8-inch corrugated round bar which was prevented from settling with the concrete. The concrete in this beam was unusually good, as there were no visible tension cracks at 8000 lb. Two tension cracks were visible at 10,000 lb. At 17,000 lb., u = 290, v = 102, the north end of the bar began to slip. At 17,600 lb., the south end of the bar began to slip. At 22,000 lb., u = 370, v = 131, the beam failed in bond at the north end followed by diagonal tension. At this load, the north end slip was 0.0024 inch and the south end slip was 0.0002 inch.

Group 4.

The two beams in this group were reinforced with one 1-inch plain round bar. The beams were made upright in the

ordinary manner, and they serve as a basis of comparison for the beams in Groups 3 and 5, and the beams in Group 6 which were reinforced with a single bar bent up in the outer thirds of the beam. Figures 16 and 26 show views of these beams after failure. Figure 53 shows the load-deflection diagrams, and Figures 60 and 96 show the load-end slip diagrams for these beams.

Beam No. 1085.1:- The first outer crack appeared at 8,000 lb. At 12,000 lb., u = 235, v = 74, the north end of the bar began to slip. At 15,000 lb., the south end of the bar began to slip and the north end slip was 0.0002 inch. At 16,000 lb., the north end of the bar began to slip at a rapid rate when the end slip was 0.0004 inch. At 16,900 lb., u = 324, v = 102, the maximum load was reached. At this load the north end slip was 0.03 inch and the south end slip was 0.0002 inch. The beam failed in bond at the north end.

Beam No. 1085.2:- At 8,000 lb., two tension cracks were visible. At 17,000 lb., u = 326, v = 102, the north end of the bar began to slip. At 18,600 lb., the south end of the bar began to slip, and the north end slip was 0.0002 in. At 19,600 lb., the north end of the bar began to slip at a rapid rate. The beam failed in bond at the north end followed by diagonal tension at a maximum load of 21,800 lb., u = 413, v = 130. At this load the north end slip was 0.045 in. and the south end slip was 0.0001 in.

Group 5.

Effect of End Anchorage upon Bond Action:- The beams in this group, No. 1086.1 and 1086.2, were reinforced with one 1-in. plain round bar with the ends anchored by 90° bends over the supports. See Figure 5 for details of these beams. The bars were bent hot to a radius of 2 in. and the bend extended 4 in. above the upper edge of the bar. The slip was measured by welding two 1/4-in. steel bars to the reinforcing bar, and extending them to a point outside the end of the beam. These 1/4-in. bars were inclosed in a 5/8-in. gas pipe when the beams were made, so that they were not in contact with the concrete at any point and were free to move in any direction when the bar slipped. Three dials, indicated by the circles with the numbers 1, 2, 3, inside as shown in Figure 82 , were placed at each end of the beam and the slip was measured in three directions. The arrow-head attached to each circle shows the direction of the slip at that point. Figure 23 shows a view of these beams after failure. Figure 54 shows the load-deflection diagrams, and Figure 82 and 83 show the load-end slip diagrams.

Beam No. 1086.1:- At 8,000 lb., a tension crack extended to the middle of the beam. At 12,000 lb., u = 235, v = 74, both ends of the bar began to slip at dials 1. At 13,000 lb., the north end of the bar began to slip at dial 2 . At 15,000 lb., the north end of the bar began to slip at dial 3, and the crack outside the north load point had turned in a diagonal direction toward the load point. At 22,000 lb., u = 418, v = 131, the maximum

load was reached. At this load, the slip at the north end was 0.0175 in. at dial 1, 0.0105 in. at dial 2 , 0.035 in. at dial 3 ; and the slip at the south end was 0.0005 at dial 1, and slip began at dial 2 , while dial 3 did not show any movement throughout the test. When the maximum load was reached, the load did not drop off suddenly as was the case in the beams with the straight bars. After the testing machine head was run down for several minutes and the beam had deflected 0.35 in., the beam was still holding 20,000 lb. load, showing that the bends were effective in preventing a total collapse. At this load of 20,000 lb., the slip at the north end was 0.11 in. at dial 1 , at dial 2 the 1/4-in. bar had slipped past the plunger of the dial, and 0.35 in. at dial 3 ; at the south end, the slip was 0.0009 in. at dial 1 , and 0.0004 in. at dial 2 . The beam failed in bond at the north end followed by diagonal tension.

Beam No. 1086.2:- Two tension cracks were visible at 8,000 lb. At 12,000 lb., u = 235, v = 74, the north end of the bar began to slip at dial 1 . At 20,000 lb., the south end of the bar began to slip at dial 1 , and the north end slip was 0.0004 in. at dial 1. At 22,650 lb., slip began at the south end at dial 2 . Dial 3 at the south end did not show any movement throughout the test. At 23,280 lb., the maximum load was reached. At this load, the deflection of the beam was 0.350 in., the slip at the north end was 0.0019 in. at dial 1 , and slip began at dials 2 and 3 , the slip at the south end was 0.0002 in. at dial 1 and 0.0001 in. at dial 2. The bends at the ends

of the bar were much more effective in this beam than in beam No. 1086.1. The head of the testing machine was run down after the maximum load was reached until the beam had deflected 0.5 in. at the center, and the beam was still holding a load of 22,900 lb. at this load, the slip at the north end was 0.0031 at dial 1, 0.0004 in. at dial 2, and 0.002 in. at dial 3. The slip at the south end did not increase after the maximum load was reached. The steel in this beam reached the yield point and the computed compressive stress in the concrete was near the ultimate strength.

Group 6.

Bond Action with Bent up Bars:- The beams in this group, No. 1087.1 to 1088.2 inclusive and No. 1095.1 to 1096.2 inclusive, were made to study bond action with bent up bars. Four beams were reinforced with one 1-in. plain round bar bent up in the outer thirds of the beam, and four beams were reinforced with two 3/4-in. plain round bars, one bar bent up and one straight. Figures 16 to 26 show views of the beams after failure. Figures 45 to 59 show the load-deflection diagrams, and Figure 60 to 96 show the load-end slip diagrams.

Beam No. 1087.2:- This beam was reinforced with one 1-in. plain round bar bent up half way between the load point and support. At 8,000 lb., two tension cracks were visible. At 16,000 lb., $u = 308$, $v = 97$, the north end of the bar began to slip. At this load, the crack outside the north load point had extended above the middle of the beam and was turning diagonally toward the load point. At 17,400 lb., the south end of the bar began to slip and

the north end slip was 0.0001 in. At this load the north end of the bar began to slip at a rapid rate, and the maximum load was reached at 19,000 lb., u = 362, v = 114. At the maximum load, the north end slip was 0.0072 in. and the south end slip was 0.0001 in. The beam failed in bond at the north end followed by diagonal tension.

Beam No. 1088.1:- This beam was reinforced with two 3/4 in. plain round bars, one straight and one bent up half way between the load point and support. The end slip of both bars was measured. Two tension cracks were visible at 8,000 lb. At this load u = 108, v = 51, the south end of the straight bar began to slip. At 10,000 lb., the north end of the straight bar began to slip. At 20,000 lb., the south end of the bent up bar began to slip, the south end of the straight bar had slipped 0.0001 in. and the north end of the straight bar had slipped 0.0004 in. At 22,000 lb., the north end of the bent up bar began to slip, the north end of the straight bar had slipped 0.0005 in., the south end of the bent up bar had slipped 0.0005 in., and the south end of the straight bar had slipped 0.001 in. The maximum load was 23,460 lb., u = 296, v = 139. At this load the south end of the straight bar had slipped 0.008 in., the south end of the bent bar had slipped 0.007 in., the north end of the straight bar had slipped 0.0006 in., and the north end of the bent bar had slipped 0.0001 in. The beam failed in bond at the south end.

Beam No. 1088.2:- This beam was similar to No. 1088.1. Three tension cracks were visible at 10,000 lb. At 12,000 lb.,

u = 157, v = 74, the south end of the straight bar began to slip. At 16,000 lb., the south end of the bent bar began to slip and the south end of the straight bar had slipped 0.0002 in. At 20,000 lb., the north end of the straight bar began to slip. The north end of the bent bar did not slip. The maximum load was 22,960 lb., u = 290, v = 136. At this load, the south end of the straight bar had slipped 0.001 in., the south end of the bent bar had slipped 0.0007 in., and the north end of the straight bar had slipped 0.0001 in. At the maximum load, a long diagonal crack opened up at the south end of the beam and crossed the point where the bar was bent up. The beam failed in bond at the south end followed by diagonal tension.

Beam No. 1095.1:- This beam was reinforced with one 1-in. plain round bar bent up 3 in. outside the load points and continued to the ends of the beam at a point 2 in. below the top face of the beam. At 8,000 lb., three tension cracks were visible. At 10,000 lb., u = 198, v = 62, the south end of the bar began to slip. At 14,000 lb., a tension crack opened up outside the north load point and the north end of the bar began to slip at a rapid rate. The maximum load was reached at 15,300 lb., u = 293, v = 92. At this load, the north end slip was 0.004 in. and the south end slip was 0.0004 in. The beam failed in bond at the north end.

Beam No. 1095.2:- This beam was similar to No. 1095.1. At 8,000 lb. four tension cracks were visible. At 10,000 lb., u = 198, v = 62, the south end of the bar began to slip. The

beam failed at 11,200 lb., u = 220, v = 69. At this load the north end slip was 0.0011 in. The south end of the bar did not slip. The beam failed in bond at the south end.

Beam No. 1096.1:- This beam was reinforced with two 3/4-in. plain round bars, one bar straight and one bar bent up 3 in. outside of the load points and continued to the ends of the beam 2 in. below the top face. At 8,000 lb., two tension cracks were visible. At 14,000 lb., u = 181, v = 85, the south end of the bent and straight bars began to slip simultaneously. The maximum load was reached at 15,300 lb., u = 197, v = 93. At this load the south end slip was 0.034 in. for both straight and bent up bars. The north end of the bars did not slip. At the maximum load, diagonal tension cracks opened up in the south third of the beam. The beam failed in bond at the south end followed by diagonal tension.

Beam No. 1096.2:- This beam was similar to No. 1096.1. At 8,000 lb., one tension crack was visible. At 16,000 lb., u = 205, v = 97, the bent bar began to slip at both ends, and the south end of the straight bar began to slip. The maximum load was reached at 21,700 lb., u = 275, v = 129. At this load, the bent up bar had slipped 0.01 in. at the south end and 0.0064 in. at the north end, and the straight bar had slipped 0.01 in. at the south end. The north end of the straight bar did not slip. The beam failed in bond at the south end followed by diagonal tension.

Group 7

The beams in this group, No. 1089.1 and 1089.2, were reinforced with two 3/4-in. plain round bars continued straight to the ends of the beam. These beams serve as a basis of comparison for the beams with one bar straight and one bent up. The end slip of both bars was measured to determine the distribution of the bond stress between the two bars.

Beam No. 1089.1:- At 10,000 lb., two tension cracks were visible. At 16,000 lb., u = 205, v = 97, both bars began to slip at the north and south ends simultaneously. At 18,000 lb., a tension crack opened up outside each load point and both bars had slipped 0.0001 in. at each end. At 22,000 lb., the north ends of the bars began to slip at a rapid rate. The maximum load was reached at 24,450 lb., u = 308, v = 145. At this load the west bar had slipped 0.005 in. at the north end and 0.0013 in. at the south end; the east bar had slipped 0.0045 in. at the north end and 0.0008 in. at the south end. The beam failed in bond at the north end followed by diagonal tension.

Beam No. 1089.2:- This beam was similar to No. 1089.1. At 8,000 lb., two tension cracks were visible. At 12,900 lb., the north end of the east bar began to slip. At this load u = 157 and v = 74. At 16,000 lb., both bars began to slip at the south end, and the north end of the east bar had slipped 0.0002 in. At 18,000 lb., the north end of the west bar began to slip and the north end of the east bar had slipped 0.0002 in., both bars had slipped 0.0001 in. at the south end. The maximum load was reached at 22,300 lb., u = 282 and v = 132. At this load, the

slip at the north end was 0.014 in. at the west bar and 0.0098 in. at the east bar; the slip at the south end of the west bar was 0.0008 in. and 0.0002 in. at the south end of the east bar. The beam failed in bond at the north end.

Figure 22 shows a view of these beams after failure. Figure 56 shows the load-deflection diagrams, and Figure 87 and 88 the load-end slip diagrams.

21. Discussion and Comparison of Results:- Considerable variation was found in the results of the tests, nevertheless, they are interesting and instructive. If such variation is found in laboratory tests where the specimens are fabricated with considerable care, it gives a warning as to what we may expect in practical construction where such care is not always taken. There were not enough specimens tested to draw any definite conclusions, and it was frequently the case that the individual variation found in specimens of similar fabrication was greater than that for two specimens of different fabrication.

All of the 8 x 12 in. beams were tested with a car spring under one end, and the 10 x 12 in. beams were tested on solid cast iron rocker supports. The car spring support put the beam under a more severe condition than the solid support. By the time the maximum load was reached, considerable energy was stored in the spring, and the condition of a free dead load capable of following up the deflection of the beam was produced. With the solid supports, the head of the testing machine was not free to follow up the deflection of the beam when the maximum

load was reached. This accounts for the manner in which the narrow beams were broken up at failure.

Failure did not always occur at the end of the beam where slip first began. Frequently the end of the bar which slipped last would pass the other end in amount of slip and cause of failure of the beam. In some of the tests, both ends of the bar began to slip simultaneously, but one end would slip at a faster rate than the other and failure would occur at the end with the greater slip.

These beams were designed so as to fail in bond, and a beam reinforced with a single bar would never be found in practice. With the percentage of steel constant, the use of several small bars will make a stronger beam than one reinforced with a single bar. Distributing the steel over the width of the beam by using small bars gives a more uniform distribution of the shearing stress just above the steel. In addition, the smaller bars will have more surface in contact with the concrete than the single large bar, and it will require a greater load to produce a given bond stress on the small bars than on the single large bar.

Upon examination of the photographs of the beams, Figures 16 to 26, it will be seen that the beams were still holding up under the load after a crack had opened up to within a short distance from the top of the beam. Figure 7 shows a typical crack of this nature. The crack cb has opened up to the point b. The part of the beam (L) on the left of the crack tends to move upward with respect to the part (R) on the right of the

crack. The total vertical shear must be resisted by the uncracked part of the beam ab and by the stiffness of the longitudinal bars. The total tensile stress in the bars at d must be taken

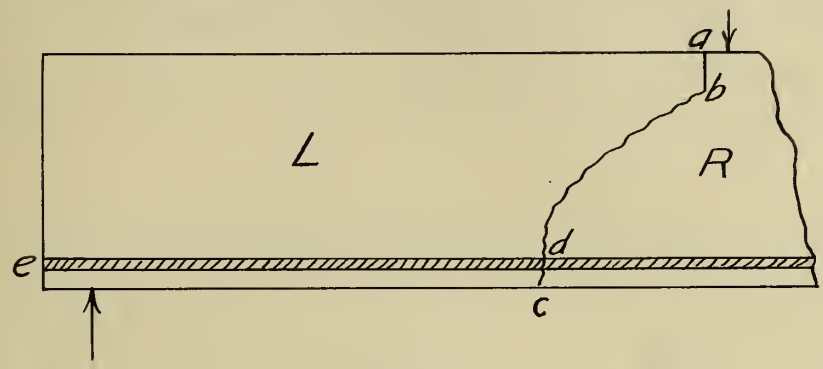


Figure 7.

Distribution of Vertical Shear after Formation of Crack.

off by bond in the length de which is a similar condition to that in a pull-out specimen. The compression stresses acting on ab are at right angles to the shear, and this being a favorable condition, a large part of the total shear may be taken by the section ab without causing failure. The part of the total vertical shear that is transmitted throughthe longitudinal bars tends to split the concrete along the plane of the reinforcing bar from d to e. As soon as this action takes place, the bond on the length de is destroyed.

Diagonal Tension and Bond Failures in Beams without Web Reinforcement; Bars Straight:- Although diagonal tension and bond are two distinct stresses and either may be the cause of primary failure in a beam, they are so intimately related as to warrant joint treatment under one heading. In a beam test, it is frequently difficult to tell whether the primary cause of a

failure is diagonal tension or inadequate bond resistance. It is the opinion of the writer, after making the tests herein described, that many beam failures which have been attributed to diagonal tension, were primarily bond failures.

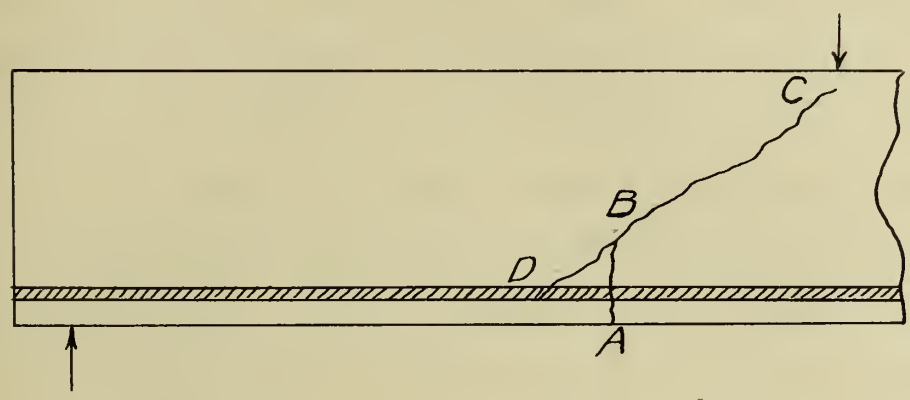


Figure 8.

Sketch Showing Diagonal Tension and Bond Failure.

Figure 8 represents a section of a beam under load. Suppose that a vertical anti-stretch crack AB has formed. If the reinforcing bar begins to slip throughout its length from the crack AB to the end of the beam, this allows the crack to open up and the concrete in this region of the beam is subjected to severe tensile stresses. As a result, the diagonal crack DC forms at right angles to the direction of the maximum diagonal tension, and the beam finally fails by diagonal tension.

On the other hand, suppose that the ends of the bars have not slipped but that the crack AB has formed and developed into a diagonal crack BC. This action concentrates a high

tensile stress in the steel bar where it is crossed by the crack. This stress may be sufficient to cause slipping from the crack to the end of the beam and a bond failure will result. In some of the beam tests, it was difficult to tell whether the end slip of the bar allowed the diagonal crack to open up or whether the formation of the diagonal crack caused the end slip.

Group 1, Time Tests:- It is difficult to make an exact comparison of the results of these tests. At first, it was the intention to determine the effect of a continued load after the end slip was 0.001 in. After three beams were tested it was decided that 0.001 in. was too large a value to use for the first slip. The different types of bars had different lengths of perimeters, and when the bond stress was the same on two different types of bar the unit shear would be larger in one beam than in the other. It was impossible to test all these beams at the same age, and this introduces another variable. The age at test varied from 182 to 250 days. However, it is doubtful if the beams increased in strength after 180 days as they were stored in the laboratory in a dry condition after that time. A study of the time-end slip diagrams for these beams furnishes the best comparison of the action of plain and deformed bars under continued load after end slip occurred. Beam No. 2 reinforced with a plain round bar, No. 4 with a corrugated round, No. 6 with a square Hevemeyer, and No. 8 with a twisted square were loaded to approximately the same bond stress. All of these bars continued to slip with continued load except the corrugated round.

The average bond stress at first end slip in two tests of each type of bar was 234 lb. per sq. in. for the corrugated round, 224 lb. per sq. in. for the plain round, 186 for the twisted square, and 180 lb. per sq. in. for the square Havemeyer. The highest individual value was 245 lb. per sq. in. with a corrugated round, and the lowest value was 125 lb. per sq. in. with a square Havemeyer. The average for all bars was 206 lb. per sq. in.

Group 2. 60-Day Concrete, Plain Round Bars:- The three beams in this group developed an average bond stress at first end slip of 221 lb. per sq. in., with a high value of 270 lb. per sq. in. and low value of 178 lb. per sq. in. The average value was 224 lb. per sq. in. for the beams in Group 1 with plain round bars and tested at an average age of 207 days. Beam No. SC7 in Group 2 failed in 119 hours under a continued load which caused an end slip of 0.0002 in.

Group 4:- The two beams in this group were reinforced with one plain round bar, and serve as a basis of comparison for the beams made upside down. One of these beams developed an ultimate bond stress of 413 lb. per sq. in. which was the highest value obtained in the tests, except the bars with end anchorage. The average bond stress at first end slip was 280 lb. per sq. in. and at maximum load 352 lb. per sq. in.

Group 3:- These beams were tested to show the effect of settlement with restrained bars. Beams No. 1081.1, 1081.2, and 1081.3 were reinforced with one plain round bar free to settle with the concrete. The average bond stress at first end slip

was 198 lb. per sq. in. as compared with 280 lb. per sq. in. for the beams made upright, and at maximum load was 283 lb. per sq. in. as compared with 352 lb. per sq. in. for the beams made upright.

Beams No. 1082.1 and 1082.2 were reinforced with a plain round bar which was prevented from settling. The average bond stress at first end slip was 216 lb. per sq.in. as compared with 280 lb. per sq. in. for the beams made upright, and at maximum load was 250 lb. per sq. in. as compared with 352 lb. per sq. in. for the beams made upright.

Beams No. 1083.1 and 1083.2 were reinforced with corrugated round bars which were free to settle. The average bond stress at first end slip was 198 lb. per sq. in. as compared with 198 lb. per sq. in. for the plain bars free to settle, and at maximum load was 386 lb. per sq. in. as compared with 283 lb. per sq. in. for the plain bars.

Beams No. 1084.1 and 1084.2 were reinforced with corrugated round bars prevented from settling. The average bond stress at first end slip was 265 lb. per sq. in. as compared with 198 lb. per sq. in. for the same bar free to settle, and at maximum load was 308 lb. per sq. in. as compared with 386 lb. per sq. in. for the same bar free to settle.

Group 5, End Anchorage:- These beams No. 1086.1 and 1086.2 were reinforced with plain round bars anchored at the ends with 90° bends. The average bond stress at first end slip was 235 lb. per sq. in. as compared with 280 lb. per sq. in. for

the plain straight bar, and at maximum load was 412 lb. per sq. in. as compared with 352 lb. per sq. in. for the plain straight bar.

Group 6, Bent Up Bars:- Although the formula for bond stress with straight bars is not applicable to beams with anchored or bent up bars, it is used to calculate the bond stress in these beams and the nominal values so obtained serve as a basis of comparison with the values for straight bars.

Beam No. 1087.2:- The bond stress in this beam at first end slip was 308 lb. per sq. in. as compared with 280 lb. per sq. in. for the plain straight bar, and at maximum load was 346 lb. per sq. in. as compared with 352 lb. per sq. in. for the plain straight bar. The bar in this beam was bent up too near the support to be effective in resisting diagonal tension.

Beams No. 1088.1 and 1088.2:- The average bond stress at first end slip was 133 lb. per sq. in. as compared with 181 lb. per sq. in. for straight bars, and at maximum load was 282 lb. per sq. in. as compared with 283 lb. per sq. in. for straight bars. The bars were bent up too near the support to be effective in resisting diagonal tension and nothing was gained by bending up the bars.

Beams No. 1095.1 and 1095.2:- The average bond stress at first end slip was 198 lb. per sq. in. as compared with 181 lb. per sq. in. for the straight bar, and at maximum load was 256 lb. per sq. in. as compared with 283 for the straight bars. These beams were weakened by bending up the bars too near the

load points.

Group 8.-Time Tests, Effect of Stirrups on Bond Action:- Beams No. 1091, 1092, 1093, and 1094, comprised this group. If the results of these beams as given in Table 9 are compared with the results of the beams in Group 2, it will be seen that the stirrups had no noticeable effect upon the value of the bond stress at first end slip. Beam No. 1091 with stirrups did not carry any higher load than beam SC7 without stirrups. Referring to the Figures 89 to 92 , it will be seen that the tension cracks opened up at a stirrup as a rule and ran up the stirrup. If the stirrups are not closely spaced, this crack will extend to the top of the beam without crossing a stirrup and no advantage will be derived by the use of the stirrups.

A comparison of the data of the beams in this group with the data of the beams in Group 2 will be interesting. The beams in Group 2 were tested at the same age, had the same cross section, were reinforced with plain round bars, and had no web reinforcement. The average bond stress at first end slip in Group 2 was 221 lb. per sq. in. as compared with 179 lb. per sq. in. for Group 8. The average bond stress at maximum load was 289 lb. per sq. in. for Group 8. The average unit vertical shear was 113 lb. per sq. in. for Group 2 and 135 lb. per sq. in. for Group 8.

Relation between End Slip and Deflection:- The slip of the end of the bar at the end of the beam where failure occurred is plotted on the load-deflection diagram for each beam. The

same scale is used for deflection and end slip. It will be noticed that the first slip of the end of the bar does not have an appreciable effect upon the deflection. When the bar begins to slip at a rapid rate, the rate of deflection increases correspondingly.

Compression Tests of Cylinders:- The results of the compression tests on the 8 x 16 cylinders show considerable variation. The average maximum unit compressive stress as determined from 43 tests was 1670 lb. per sq. in. The individual values varied from 1270 lb. to 2010 lb. per. sq. in. The average modulus of elasticity as determined from 25 tests was 3,360,000 lb. per sq. in. The individual values varied from 2,060,000 to 5,550,000 lb. per sq. in.

Comparison of Bond Action in Beams and Pull-out Specimens:- Load-end slip diagrams have the same general form for beams and pull-out specimens. End slip began in the beams with straight bars when the bond stress was about 65% of the ultimate, the individual range being from 56 to 82%. End slip began in the pull-out tests when the average bond stress was about 52% of the ultimate for 3/4-in. plain round bars, 38% for the 1-in. plain round bars, 37% for the corrugated round, 52% for the square Havemeyer, and 41% for the twisted square. The average maximum unit bond stress was 400 lb. per sq. in. for 15 tests on 3/4-in. plain round bars, 530 lb. per sq. in. for 33 tests on 1-in. plain round bars, 597 lb. per sq. in. for 12 tests on the 1 1/8-in. corrugated round bars, 366 lb. per sq. in. for

3 tests on 1-in. square Havemeyer bars, and 325 lb. per sq. in. on 3 tests with 1-in. twisted square bars. The average end slip at maximum bond stress in the pull-out tests was 0.018 in. for the corrugated bars, 0.014 in. for the 1-in. plain rounds, 0.0128 in. for the 3/4-in. plain rounds, 0.087 in. for the Havemeyer, and 0.095 for the twisted square. All of the bars split the concrete blocks except the plain rounds, and for that reason the deformed bars were unable to develop their full sliding friction. Figure 44 shows the average bond stress-end slip diagrams for the pull-out specimens. The diagrams are not plotted beyond the average ultimate bond stress. A comparison of the bond stress developed in the corresponding beams and pull-out specimens can be made by reference to Table 9.

22. Conclusions:- The principal conclusions found in the discussion are as follows:

1. Too much confidence has been placed upon deformed bars. The following is quoted from a standard text book on Reinforced Concrete, "For the deformed bars having a positive grip, a working stress of 150 lbs./in.^{2} gives an ample margin." The results of the time tests show that several beams failed under a continued load which produced a bond stress of less than 300 lb. per sq. in. A factor of safety of 2 is too small a value for a material as variable as reinforced concrete. In many of the tests, the deformed bars gave results inferior to those of the plain round bars.

2. The desirable type of deformed bar is one having

projections with surfaces at right angles to the length of the bar. A deformed bar constructed upon these lines will show some advantages over the plain round bar. Deformed bars which depend upon wedging action do not seem to have any superiority over plain round bars.

3. The anchorage of the ends of the bar by means of bends is an effective means of preventing a sudden failure in a beam, but had no effect upon the first slip of the ends of the bar.

4. A continued load which produces an end slip of 0.0002 in. in a beam made of the kind of concrete used in these tests and loaded at the age of 60 days, will very likely cause failure of the beam regardless of the kind of reinforcing bar used.

5. End slip in beams begins at about the same bond stress for plain and deformed bars having the same general shape of cross-section.

6. If considerable care and judgment are not used in bending up bars, the beam will be weakened instead of strengthened.

7. There is a considerable reduction of bond strength on restrained bars which are not free to settle with the concrete as it sets. This is liable to produce serious results in continuous beams and floor slabs where the bars are bent up to take negative bending moments. This reduction of bond is not so apparent with corrugated bars, although the tests were not

of sufficient number to make this statement conclusive.

8. There was some reduction of bond due to the difference in pressure in the concrete at the top and bottom of the beam, but the tests were not of sufficient number to give any value for the amount of this reduction.

Table 6.

Individual Variations in Cylinder and Pull-Out Tests.

Beam No.	Cylinders		Pull-Out Tests.				
	Age Days	Maximum Unit Stress lbs per sq. in.	Age Da.	Bond Stress at First Slip	Bond Stress Maximum Load	Slip at Maximum Load	Kind of Bar.
1081.1			60	165	765	.013	1" Plain Round.
"	60	1800	60	275	670	.016	"
"	61	1910	60	280	690	.015	"
Average		1855		238	709	.015	
1081.2			61	160	555	.013	1 in Plain Round
"	61	1520	61	190	555	.009	"
"	61	1700	61	180	517	.015	"
Average		1610		176	542	.012	
1081.3							1 in Plain Round
"	59	1270					"
"	59	1540	59½	190	615	.005	"
Average		1405		190	615	.005	
1082.1			60	180	495	.025	1 in Plain Round
"	60	1970	60	175	380	.039	"
"	60	1460	60	110	430	.011	"
Average		1715		168	435	.026	
1082.2			61	184	685	.010	1 in plain round.
"			61	200	320	.005	"
"	60	1545	61	200	610	.009	"
Average		1545		193	539	.008	
1083.1			60	210	670	.041	1⅛ in. Corrugated ϕ
"	60	1685	60	250	615	.055	"
"	60	1960	60	210	650	.041	"
Average		1825		225	645	.046	
1083.2			60	254	561	.01	1⅛ in. Corr. Round.
"	60	1690	60	292	538	.003	"
"	60	2010	60	195	450	.005	"
Average		1850		278	582	.006	
1084.1			60	140	460		1⅛ in. Corr. Round.
"			60	140	530		"
"	60	1700	60	165	560		"
Average		1700		149	516		

Table 6.
(Continued)

Beam No.	Cylinders		Pull-Out Tests.				
	Age Days	Maximum Unit Stress lb. per sq. in.	Age Days	Bond Stress at First Slip	Bond Stress Maximum Load	Slip at Maximum Load	Kind of Bar.
1084.2			60	260	490	.009	1 1/8 Corr. Round.
"	60	1480	60	250	530	.006	"
"	60	2010	60	230	595	.007	"
Av.		1745		245	540	.007	
1085.1							
"	60	1870	60	140	600	.015	1 in. Plain Round
"	60	1565	60	355	645	.013	"
Av.		1720		246	622	.014	"
1085.2			59	285	570	.017	1 in. Plain Round
"	61	1540	59	230	465	.011	"
"	61	1890	59	185	605	.015	"
Av.		1715		230	546	.014	
1086.1			61	175	485	.008	1 in. Plain Round.
"	61	1980	61	195	495	.006	"
"	61	1780	61	185	435	.016	"
Av.		1880		183	470	.010	
1086.2			60	235	435	.014	1 in. Plain Round
"	59	1650	60	195	470	.01	"
"	59	1850	60	185	560	.012	"
Av		1750		204	488	.012	
1087.2			61	160	380	.024	1 in. Plain Round
"	61	1290	61	145	450	.01	"
"	61	1450	61	150	350	.014	"
Av.		1370		150	395	.016	
1088.1			60	130	245	.013	3/4 in. Plain Round.
"	60	1490	60	130	345	.015	"
"	60	1730	60	200	405	.013	"
Av.		1610		154	330	.014	
1088.2			61	375	665	.017	3/4 in. Plain Round
"	60	1690	61	250	445	.009	"
"	60	2010	61	240	455	.01	"
Av		1850		286	520	.012	

Table 6.
(Continued)

Beam No.	Cylinders		Pull-Out Tests.				
	Age Days	Maximum Unit Stress lb. per sq. in.	Age Days	Bond Stress at First Slip	Bond Stress at Maximum Load	Slip at Maxim. Load	Kind of Bar.
1089.1			60	205	345	.013	3/4" Plain Round
"	60	1745	60	220	305	.011	"
"	60	1875	60	110	170	.018	"
Av.		1810		177	273	.014	
1089.2			60	230	480	.01	3/4" Plain Round
"	60	1315	60	244	515	.011	"
"	60	1530	60	191	433	.009	"
Av		1420		222	475	.010	
1091			60	220	515	.012	1 in. Plain Round
"	60	1440	60	270	525	.013	"
"	60	1290	60	240	610	.010	"
Av		1365		240	548	.012	
1092			60	225	635	.026	1 1/8" Corr. Round.
"	60	1600	60	160	660	.009	"
"	60	1765	60	240	595	.013	"
Av.		1680		210	628	.016	
1093			59	135	335	.093	1 in. Twisted Square
"	61	1580	59	150	380	.170	"
"	61	1500	59	125	260	.021	"
Av.		1540		136	326	.095	
1094			60	190	340	.025	1 in. Sq. Havemeyer
"	60	1630	60	160	385	.134	"
"	60	1460	60	230	370	.130	"
Av.		1545		192	366	.087	
1095.1	60	1160	No Pull-Out Specimens				1 in. Plain Round
"							"
"							"
Av.		1160					
1095.2	60	1590	No. Pull-Out Specimens				1 in. Plain Round
"							"
"							"
Av.		1590					

Table 6.
(Continued)

Beam No.	Cylinders		Pull-Out Specimens.				
	Age Days	Maximum Unit Stress lb. per sq. in.	Age Days	Bond Stress at First Slip	Bond Stress at Max. Load.	Slip at Maximum Load	Kind of Bar.
1096.1	60	1610	No Pull-Out Specimens with this beam.				
"							
"							
Av.		1610					
1096.2		1580	No. Pull-Out Specimens with this beam.				
"							
"							
Av.		1580					

Table 7.
Compressive and Flexural Strength of Concrete.

6 x 8 x 36-in. Plain Beams.				6-in. Cubes.			
No.	From Same Batch as Beam	Age Days	Modulus of Rupture	No	From Same Batch as Beam	Age Days	Compressive Strength
1	SC 1	60	328	1	SC 4	60	1880
2	SC 7	60	354	2	"	60	1790
3	SC 4	60	307	3	"	60	1840
	Average		329		Average		1836
				1	SC 7	60	1970
				2	"	60	2010
				3	"	60	1910
					Average		1963
				1	SC 7	60	1310 *

* 8 x 16 in. Cylinder.

Table 8.
Values Used in Calculation of Stress in Steel.

Beam No.	f_c	n	q	k	z	A	M	f_s
1	1800	15	0.9	0.49	1.8	0.886	249,000	34,000
2	1600	"	0.8	0.55	2.0	0.886	217,000	30,700
3	2000	"	1.0	0.52	1.9	0.994	298,000	37,000
4	1600	"	0.8	0.50	2.0	0.994	226,000	28,400
5	1600	"	0.8	0.50	2.0	1.00	249,000	31,000
6	1800	"	0.9	0.50	2.0	1.00	245,000	30,600
7	1800	"	0.9	0.50	2.0	1.00	245,000	30,600
8	1800	"	0.9	0.50	2.0	1.00	245,000	30,600
SC1	1300	10	0.7	0.49	1.8	0.785	177,500	27,600
SC4	1600	"	0.9	0.42	1.5	0.785	217,000	32,500
SC7	1300	"	0.7	0.49	1.8	0.785	178,000	27,600
1081.1	1200	"	0.7	0.44	1.6	0.785	208,000	31,600
1081.2	900	"	0.5	0.35	1.2	0.785	155,000	22,500
1081.3	1300	"	0.8	0.46	1.7	0.785	230,000	35,000
1082.1	780	"	0.4	0.34	1.2	0.785	131,000	19,000
1082.2	1300	"	0.7	0.44	1.6	0.785	223,000	33,800
1083.1	2300	"	1.0	0.42	1.6	0.994	395,000	47,000
1083.2	2400	"	0.7	0.42	1.6	0.994	399,000	47,500
1084.1	1200	"	1.0	0.40	1.4	0.994	203,000	23,600
1084.2	1600	"	1.0	0.42	1.6	0.994	275,000	32,800
1085.1	1200	"	0.7	0.36	1.3	0.785	203,000	29,700
1085.2	1600	"	0.9	0.39	1.4	0.785	272,000	40,000
1086.1	1600	"	0.9	0.39	1.4	0.785	275,000	40,700
1086.2	1700	"	1.0	0.39	1.4	0.785	290,000	43,000
1087.2	1400	"	0.8	0.37	1.3	0.785	239,000	35,000
1088.1	1700	"	1.0	0.40	1.5	0.884	293,000	39,000
1088.2	1700	"	1.0	0.40	1.5	0.884	286,000	38,000
1089.1	1800	"	1.0	0.40	1.5	0.884	304,000	40,000
1089.2	1600	"	0.9	0.40	1.5	0.884	278,000	37,000
1091	1300	"	0.7	0.49	1.8	0.785	177,500	27,500
1092	2100	"	1.0	0.45	1.7	0.994	282,000	34,000
1093	1700	"	1.0	0.45	1.7	1.00	235,000	29,300
1094	1600	"	1.0	0.45	1.7	1.00	226,000	27,200
1095.1	1100	"	0.6	0.45	1.6	0.785	193,000	29,300
1095.2	870	"	0.6	0.45	1.6	0.785	145,000	22,000
1096.1	1160	"	0.6	0.37	1.3	0.884	194,000	25,200
1096.2	1600	"	0.9	0.40	1.5	0.884	271,000	36,000

Table 9.

Data of Reinforced Concrete Beam and Auxiliary Specimen Tests.

Data of Reinforced Concrete Beams																Compression Tests 6"x16" Cylinders		Pull-Out Tests			
Group No.	Beam No.	Longitudinal Reinforcement: Kind of Bar	Longitudinal Reinforcement: Per-cent	Stirrups Round Bars 4" apart	Mixture by Weight	Weight of Water	Dead Load on Beam	Age at Test Days	Cross Section of Beam	Load at First Tension Crack	At First slip of End of Bar: Applied Load	At First slip of End of Bar: Computed Bond Stress	At Maximum Load: Applied Load	At Maximum Load: Tensile Stress in Steel	At Maximum Load: Vertical Shearing Stress	At Maximum Load: Computed Bond Stress	Age Days	Av. of 2 Tests lb. per sq. in.	Age Days	Bond Resistance: First Slip	Bond Resistance: Maximum	Manner of Failure
1	1	One 1 1/16-in. plain round	1.11	None			750	182	8x12	8000	13350	241	20000	34,000	148	356						Bond at N. End Followed by Diagonal Tension
1	2	One 1 1/16-in. plain round	1.11	"			1130	233	8x12	6000	11000	207	17000	30,700	127	304						Bond at E. End Followed by Diagonal Tension
1	3	One 1 1/8-in corrugated round	1.24	"			800	186	8x12	8000	14350	245	24000	37,000	177	402						Bond at S. End Followed by Diagonal Tension
1	4	One 1 1/8-in. corrugated round	1.24	"			800	236	8x12	6000	13000	224	18000	28400	134	304						Beam not tested to failure
1	5	One 1-in. square Havemeyer	1.25	"			750	188	8x12	8000	15750	236	18000	31,000	134	268						Bond at South End
1	6	One 1-in. square Havemeyer	1.25	"			750	250	8x12	6000	8000	125	20000	30600	148	296						Beam not tested to failure
1	7	One 1-in. twisted square	1.25	"			750	188	8x12	6000	10000	154	20000	30600	148	296						Beam not tested to failure
1	8	One 1-in. twisted square	1.25	"			800	109	8x12	6000	14560	219	20000	30600	148	296						Bond at N. End Followed by Diagonal Tension
2	SC 1	One 1-in. plain round	0.98	"			800	60	8x12	4000	9000	178	14000	27600	106	270						Bond at South End
2	SC 4	One 1-in. plain round	0.98	"			800	60	8x12	4000	14000	270	17260	32,500	129	328						Bond and Diagonal Tension at South End
2	SC 7	One 1-in. plain round	0.98	"			800	60	8x12	4000	11000	215	14000	27600	106	270	60	1315 x				Bond at South End
3	1081.1	One 1-in. plain round	0.785	"	1-2.13-3.37	115	900	60	10x12	8000	10000	198	16400	31600	99	315	60 1/2	1855	60	238	709	Bond at North End
3	1081.2	One 1-in. plain round	0.785	"	1-2.25-3.81	105	900	61	10x12	8000	10000	198	12000	22,500	74	235	61	1610	61	176	542	Bond at North End
3	1081.3	One 1-in. plain round	0.785	"	1-2.27-3.13	100	900	59 1/2	10x12	8000	10000	198	18300	35,000	110	250	59	1405	59	190	615 ①	Bond at North End
3	1082.1	One 1-in plain round	0.785	"	1-2.20-3.64	107	900	61	10x12	8000	10000	198	10000	19000	62	198	60	1715	60	168	435	Bond at North End
3	1082.2	One 1-in plain round	0.785	"	1-2.26-3.84	100	900	60	10x12	8000	12000	235	17650	33800	106	338	60	1545 x	61	193	539	Bond at South End
3	1083.1	One 1 1/8-in corrugated round	0.99	"	1-2.18-3.60	105	900	60	10x12	8000	10000	176	23640	47000	140	397	60	1825	60	225	645	Bond at S. End Followed by Diagonal Tension
3	1083.2	One 1 1/8-in corrugated round	0.99	"	1-2.28-3.79	100	900	62	10x12	8000	12000	209	24000	47500	142	403	60	1850	60	278	582	Bond at N. End Followed by Diagonal Tension
3	1084.1	One 1 1/8-in. corrugated round	0.99	"	1-2.08-3.41	80	900	60	10x12	8000	14000	241	16000	23600	97	262	60	1700 x	60	149	516	Bond at S. End Followed by Diagonal Tension
3	1084.2	One 1 1/8-in. corrugated round	0.99	"	1-2.21-3.78	105	900	61	10x12	10000	17000	290	22000	32800	131	370	60	1745	60	245	540	Bond at N. End Followed by Diagonal Tension
4	1085.1	One 1-in. plain round	0.785	"	1-2.45-3.95	120	900	60	10x12	8000	12000	235	16900	29700	102	324	60	1720	60	246	622 ②	Bond at North End
4	1085.2	One 1-in. plain round	0.785	"	1-2.27-3.69	105	900	61	10x12	8000	17000	326	21800	40,000	130	413	61	1715	61	230	546	Bond at N. End Followed by Diagonal Tension
5	1086.1	One 1-in. plain round	0.785	"	1-2.30-3.81	100	900	60	10x12	8000	12000	235	22000	40700	131	418	61	1880	61	175	485	Bond at N. End Followed by Diagonal Tension
5	1086.2	One 1-in. plain round	0.785	"	1-2.28-3.76	100	900	60	10x12	8000	12000	235	23280	43,000	138	440	59	1750	60	204	488	Bond Followed by Tension in Steel
6	1087.1	One 1-in. plain round	0.786	"	1-2.11-3.40	90	900										60	1995 x				See Phenomena of Tests Chapter IV
6	1087.2	One 1-in. plain round	0.785	"	1-2.24-3.85	100	900	61	10x12	8000	16000	308	19000	35,000	114	362	61	1370	61	150	395	Bond at N. End Followed by Diagonal Tension
6	1088.1	Two 3/4-in. plain round	0.884	"	1-2.13-3.74	105	900	60	10x12	8000	8000	108	23460	37,000	139	296	60 1/2	1610	60	154	330	Bond at S. End.
6	1088.2	Two 3/4-in plain round	0.884	"	1-2.28-3.90	100	900	61	10x12	10000	12000	157	22960	38000	136	290	60	1850	61	286	520	Bond at S. End followed by Diag. Tension
7	1089.1	Two 3/4-in. plain round	0.884	"	1-2.18-3.58	105	900	60	10x12	10000	16000	205	24450	40000	145	308	60	1810	60	177	273	Bond at N. End followed by Diag. Tension
7	1089.2	Two 3/4-in plain round	0.884	"	1-2.23-3.75	100	900	62	10x12	8000	12000	157	22300	37000	132	282	60	1420	60	222	475	Bond at N. End.
8	1091	One 1-in. plain round	0.98	1/4 inch	1-2.23-3.73	95	800	60	8x12	6000	9500	187	14000	27500	106	270	60	1365	60	240	548	Bond at N. End Followed by Diagonal Tension
8	1092	One 1 1/8-in. corrugated round	1.24	1/4 inch	1-2.25-3.71	105	1130	60	8x12	6000	10500	188	21500	34000	161	366	60	1680	60	210	628	Bond at N. End Followed by Diagonal Tension
8	1093	One 1-in. twisted square	1.25	1/4 inch	1-2.32-3.68	95	1130	61	8x12	6000	12000	187	18500	29300	140	281	61	1540	59	136	326	Bond at N. End Followed by Diagonal Tension
8	1094	One 1-in. square Havemeyer	1.25	1/4 inch	1-2.24-3.69	100	750	60	8x12	6000	10000	154	18000	27200	134	278	60	1545	60	192	366	Bond at N. End Followed by Diagonal Tension
6	1095.1	One 1-in. plain round	0.785	None	1-2.13-3.52	100	900	61	10x12	8000	10000	198	15200	29300	92	293	60	1160 x	-	—	—	Bond at North End.
6	1095.2	One 1-in. plain round	0.785	"	1-2.14-3.58	100	900	61	10x12	8000	10000	198	11200	22,000	69	220	60	1590 x	-	—	—	Bond at South End.
6	1096.1	Two 3/4-in. plain round	0.884	"	1-2.15-3.54	100	900	60	10x12	8000	14000	181	15300	25200	93	197	60	1610 x	—	—	—	Bond at S. End followed by Diag. Tension.
6	1096.2	Two 3/4-in. plain round	0.884	"	1-2.11-3.50	95	900	60	10x12	8000	16000	205	21700	36,000	120	275	60	1580 x	—	—	—	Bond at S. End followed by Diag. Tension.

V.

DIAGRAMS AND PHOTOGRAPHS.

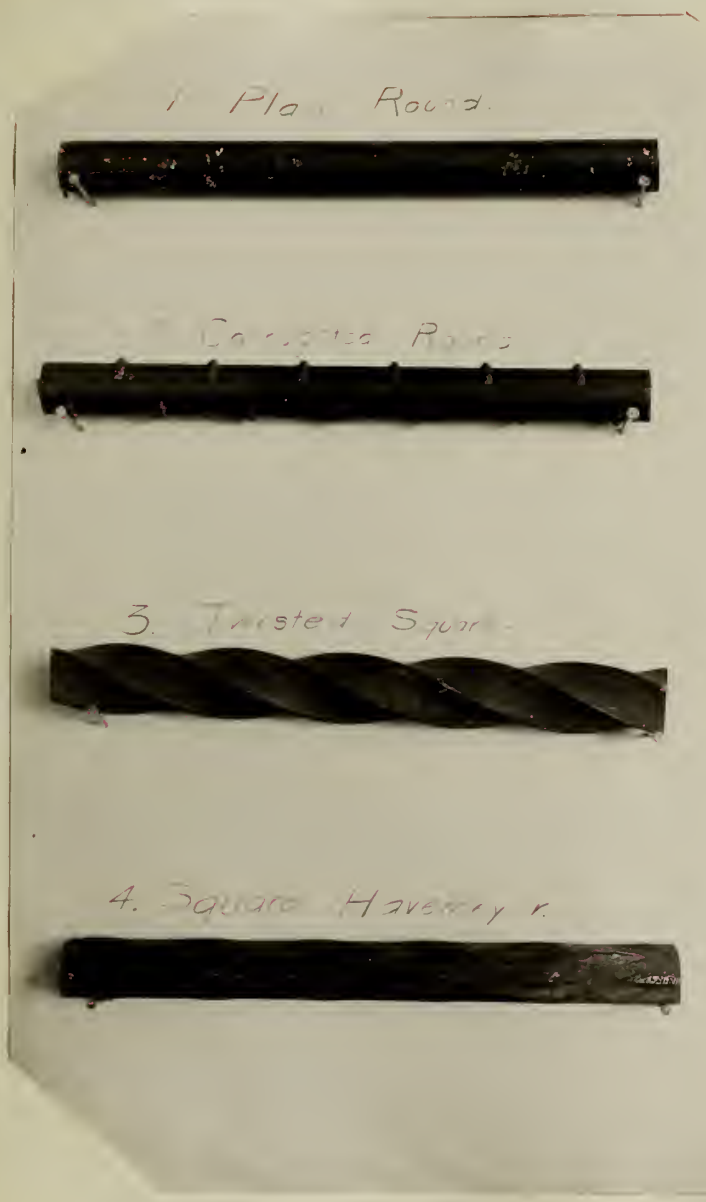


Figure 9. Types of Reinforcing Bars Used in Tests.

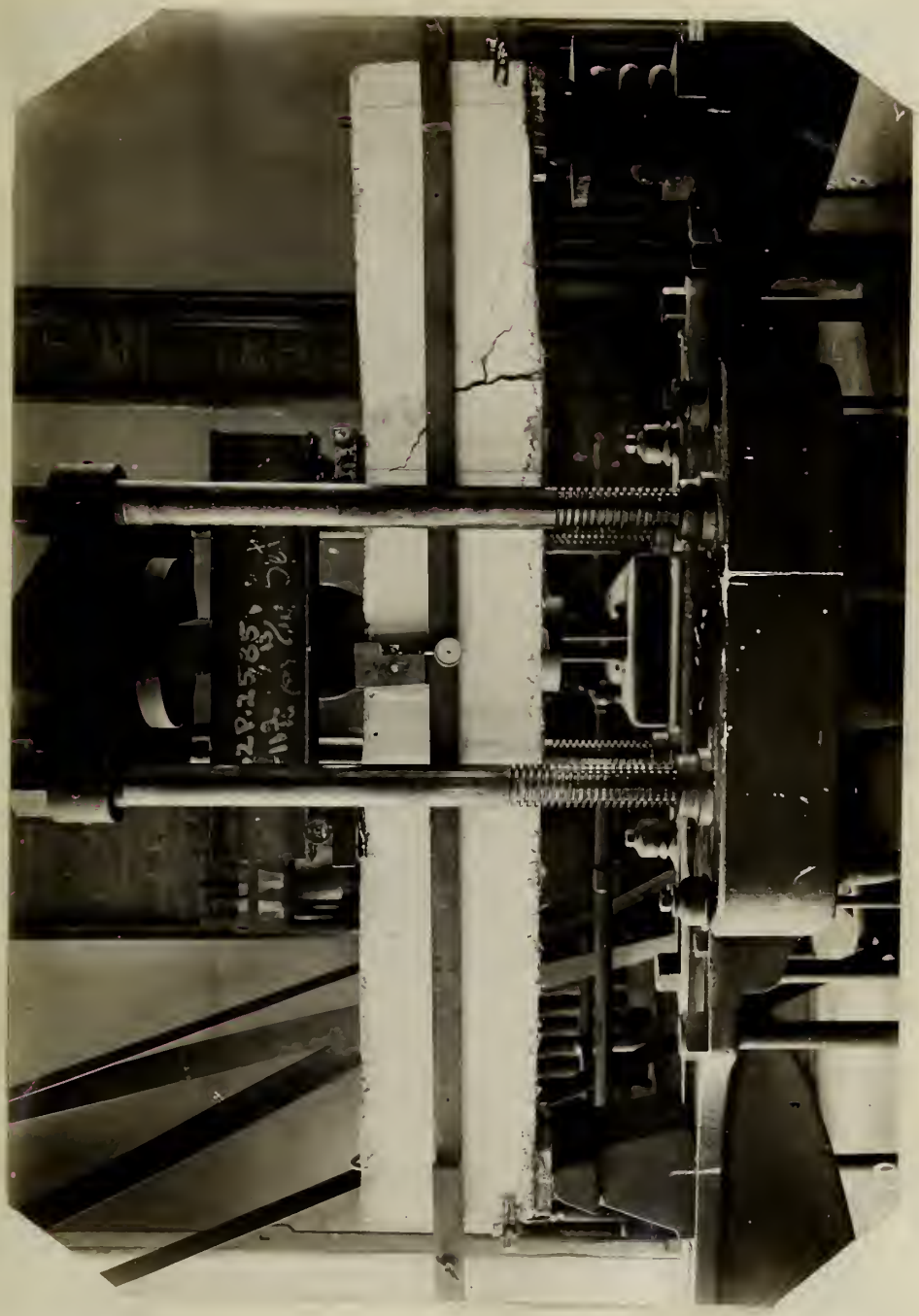


Figure 10. Beam No. 1 in Machine after Test.

Figure 11. Beam No. 3 in Machine After Test.

Figure 12. View of Tension Crack in Beam No. 5 after Continued Load for 57 Days.

Figure 13. Same Crack as in Figure 12 After Failure of Beam.

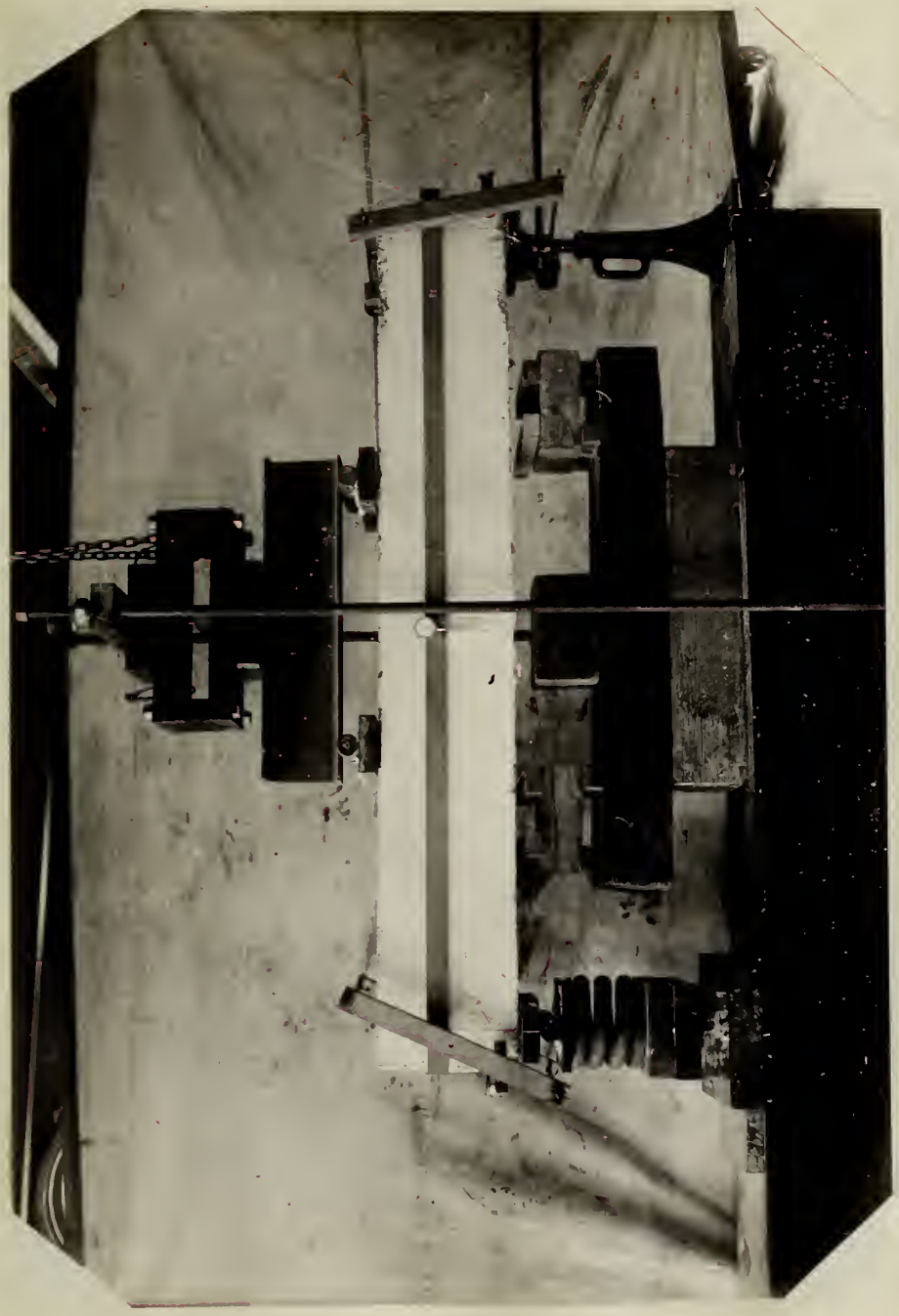


Figure 14. Dynamoter Testing Machine and Beam under Test.

Figure 15. Dynamometer Testing Machines and Beams Under Test.

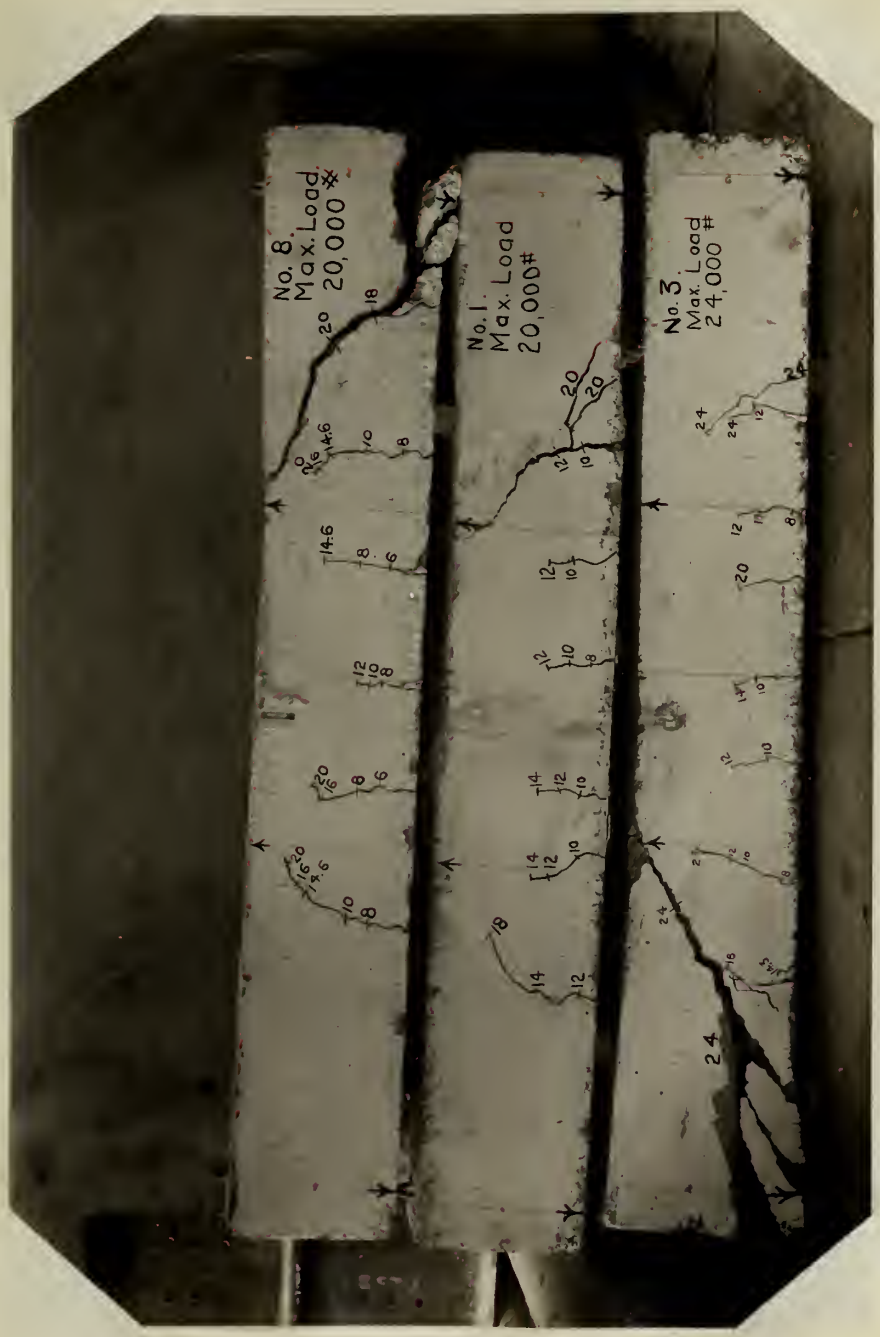


Figure 16. Reinforced Concrete Beams After Test.

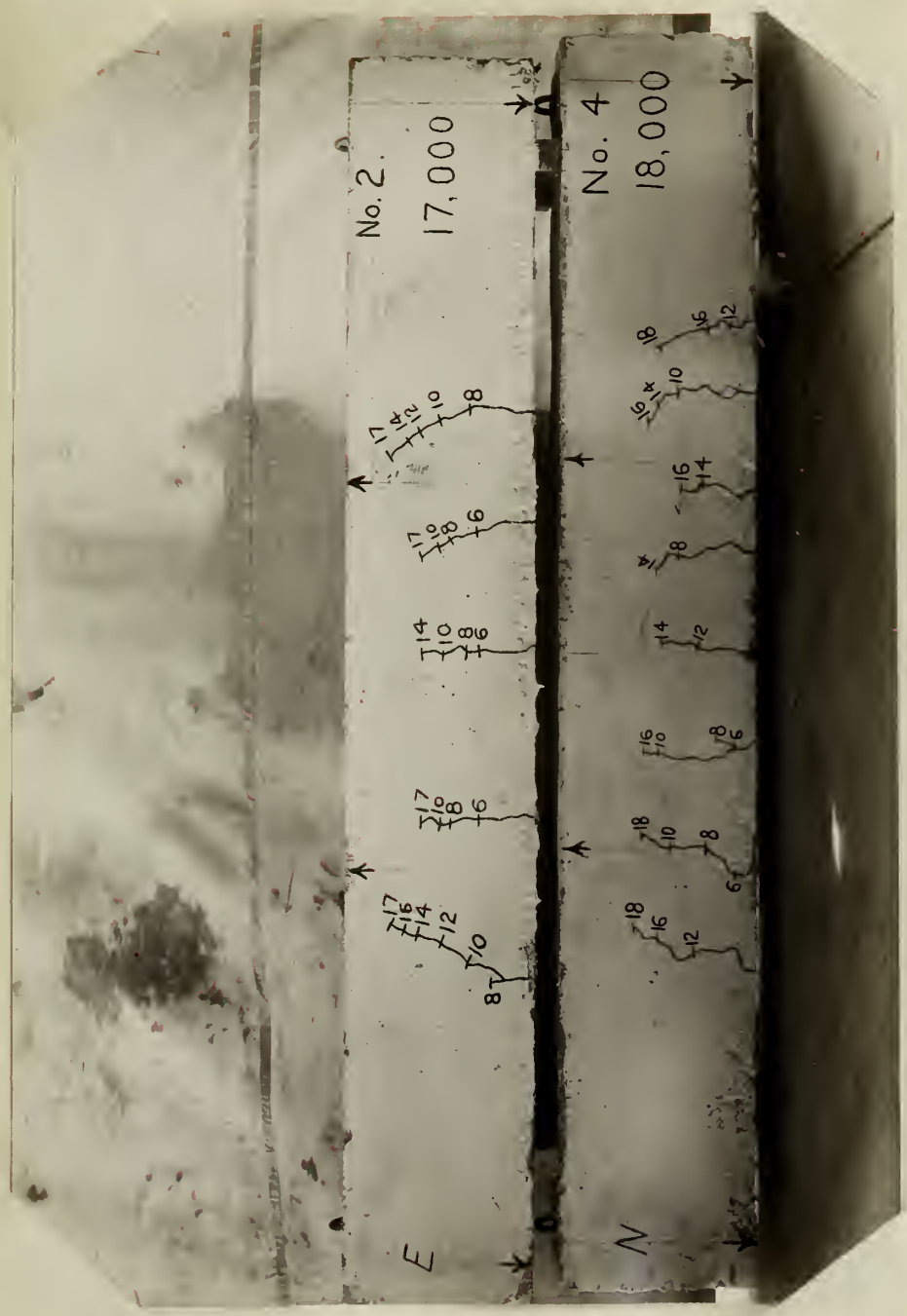


Figure 17. Reinforced Concrete Beams After Test.

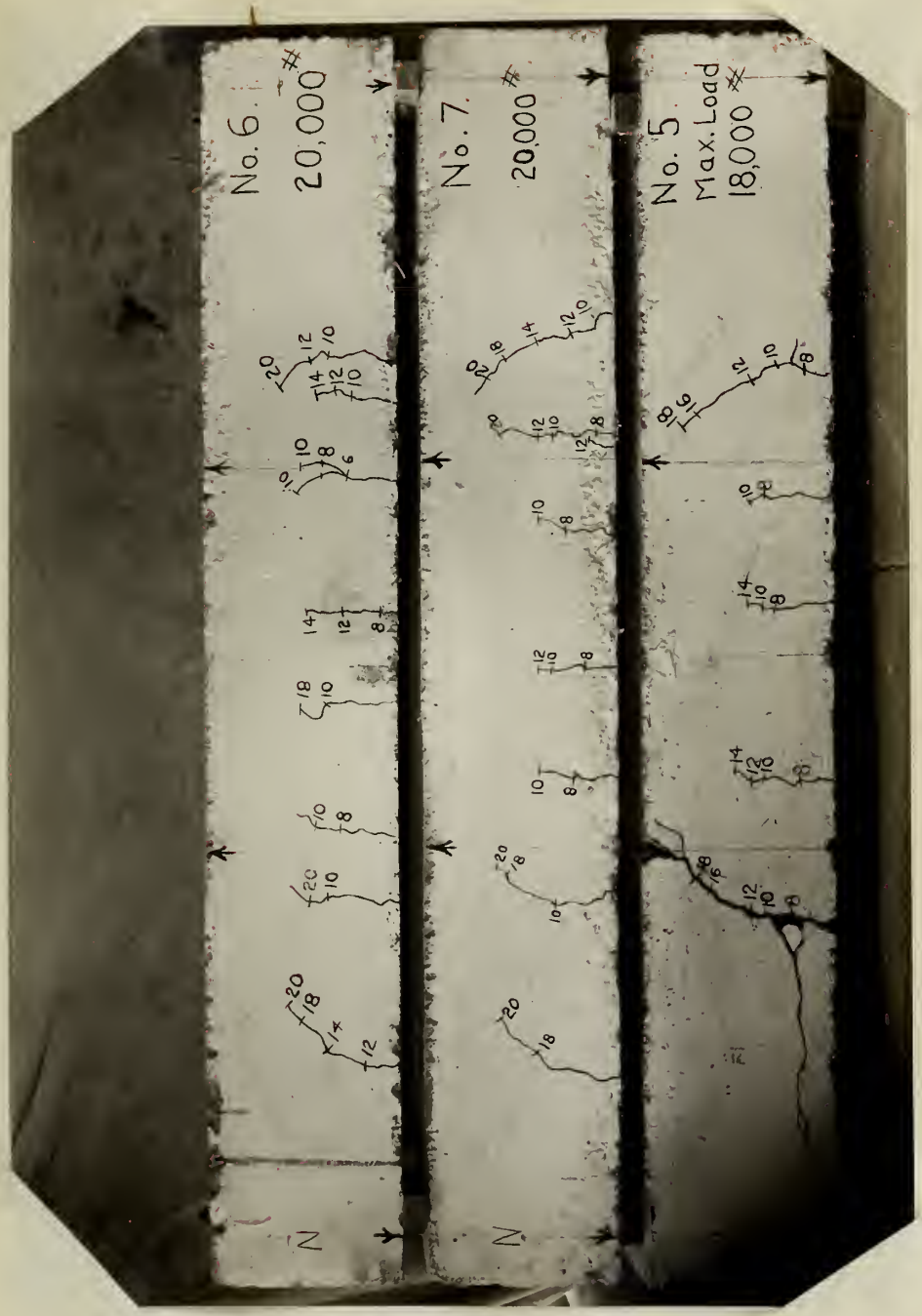


Figure 18. Reinforced Concrete Beams After Test.

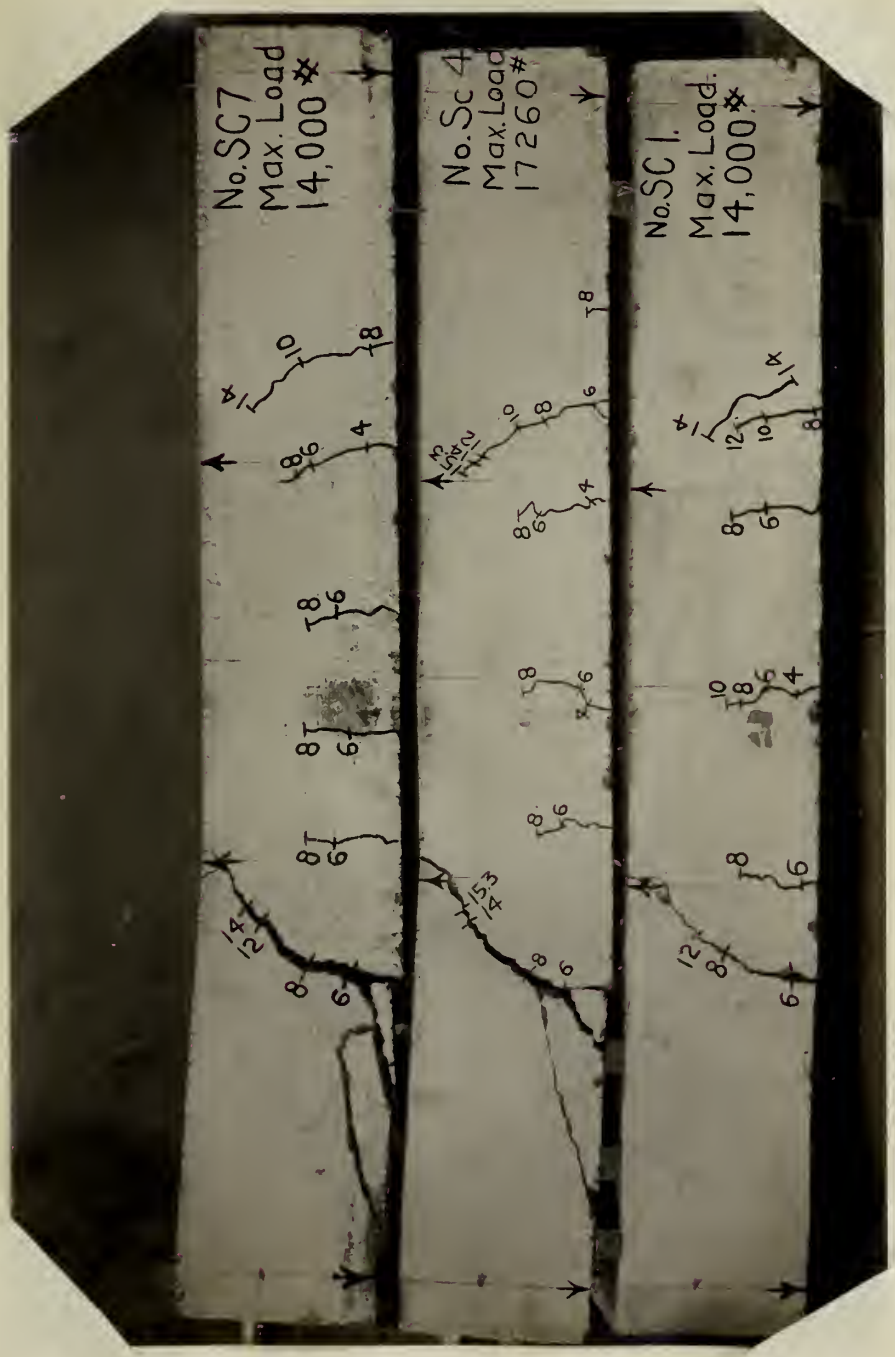


Figure 19. Reinforced Concrete Beams After Test.

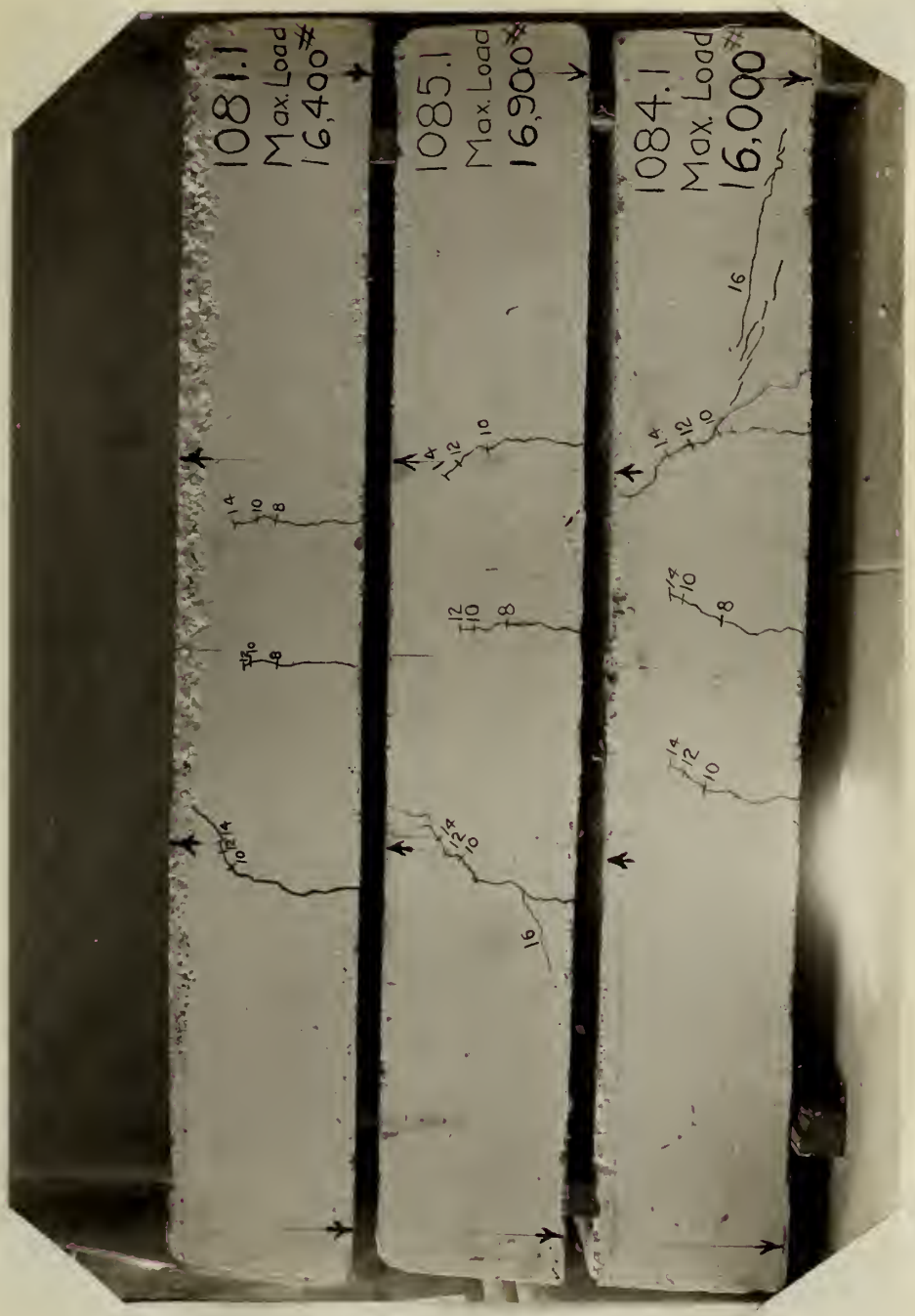


Figure 20. Reinforced Concrete Beams After Test.

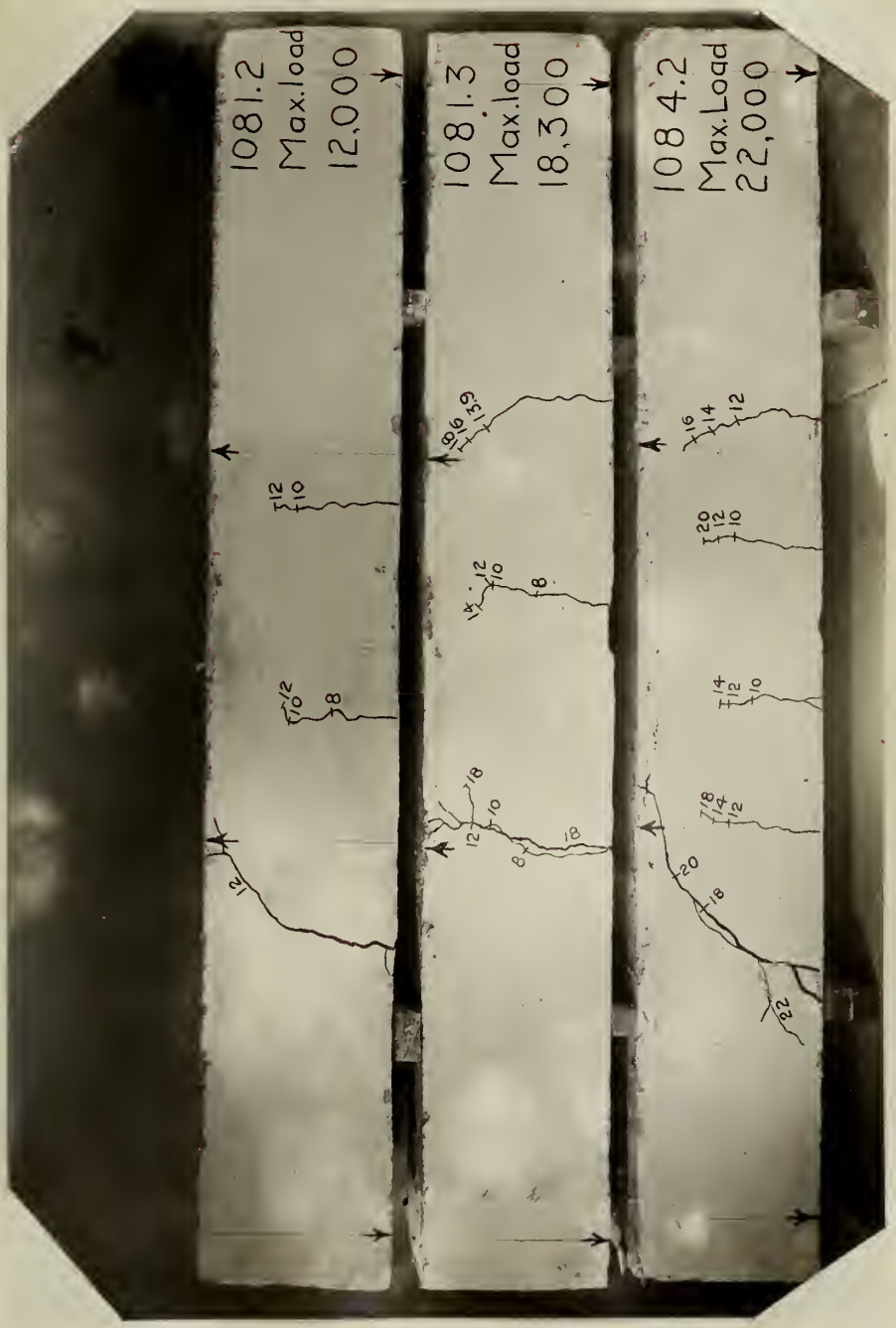


Figure 21. Reinforced Concrete Beams After Test.

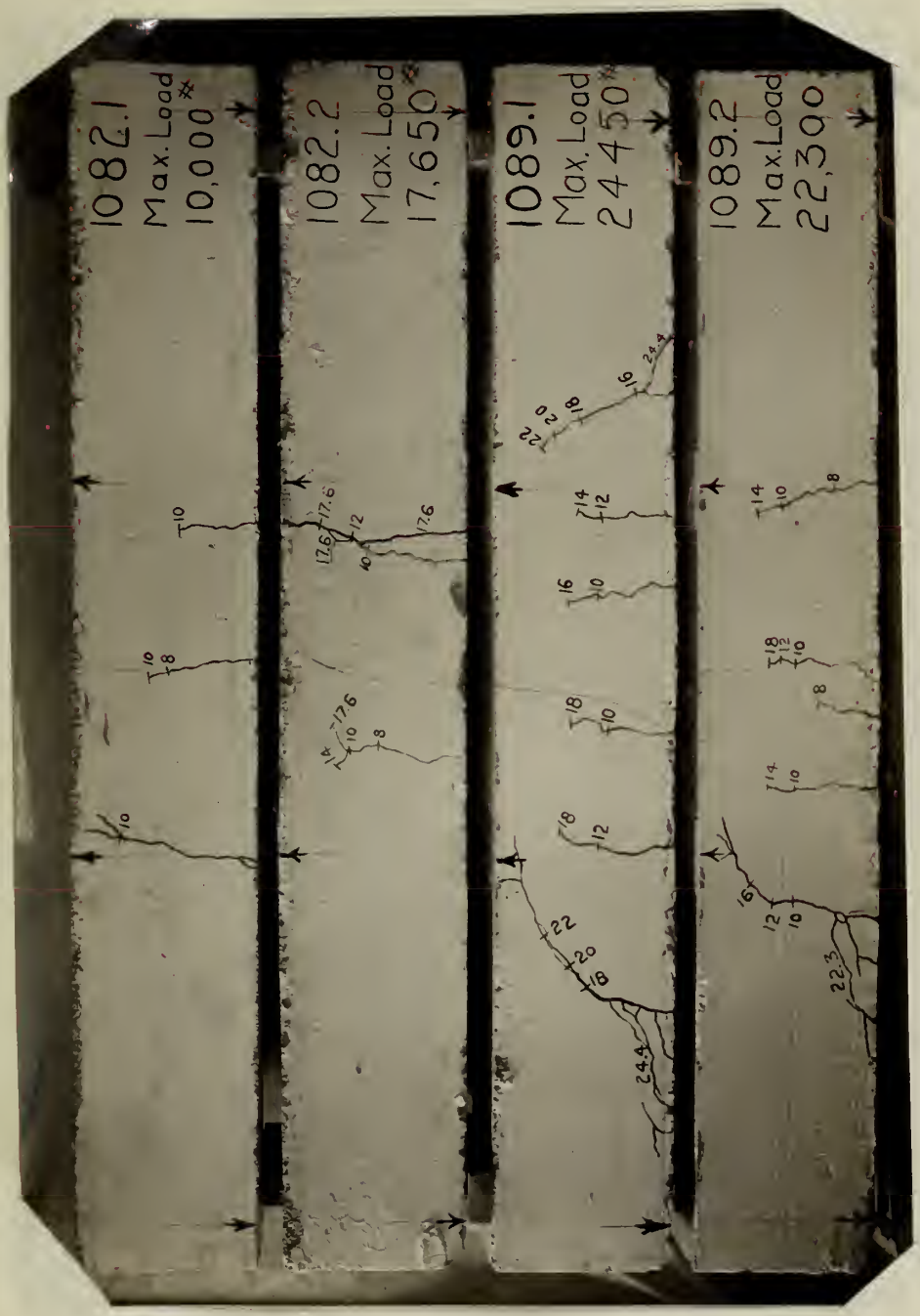


Figure 22. Reinforced Concrete Beams After Test.

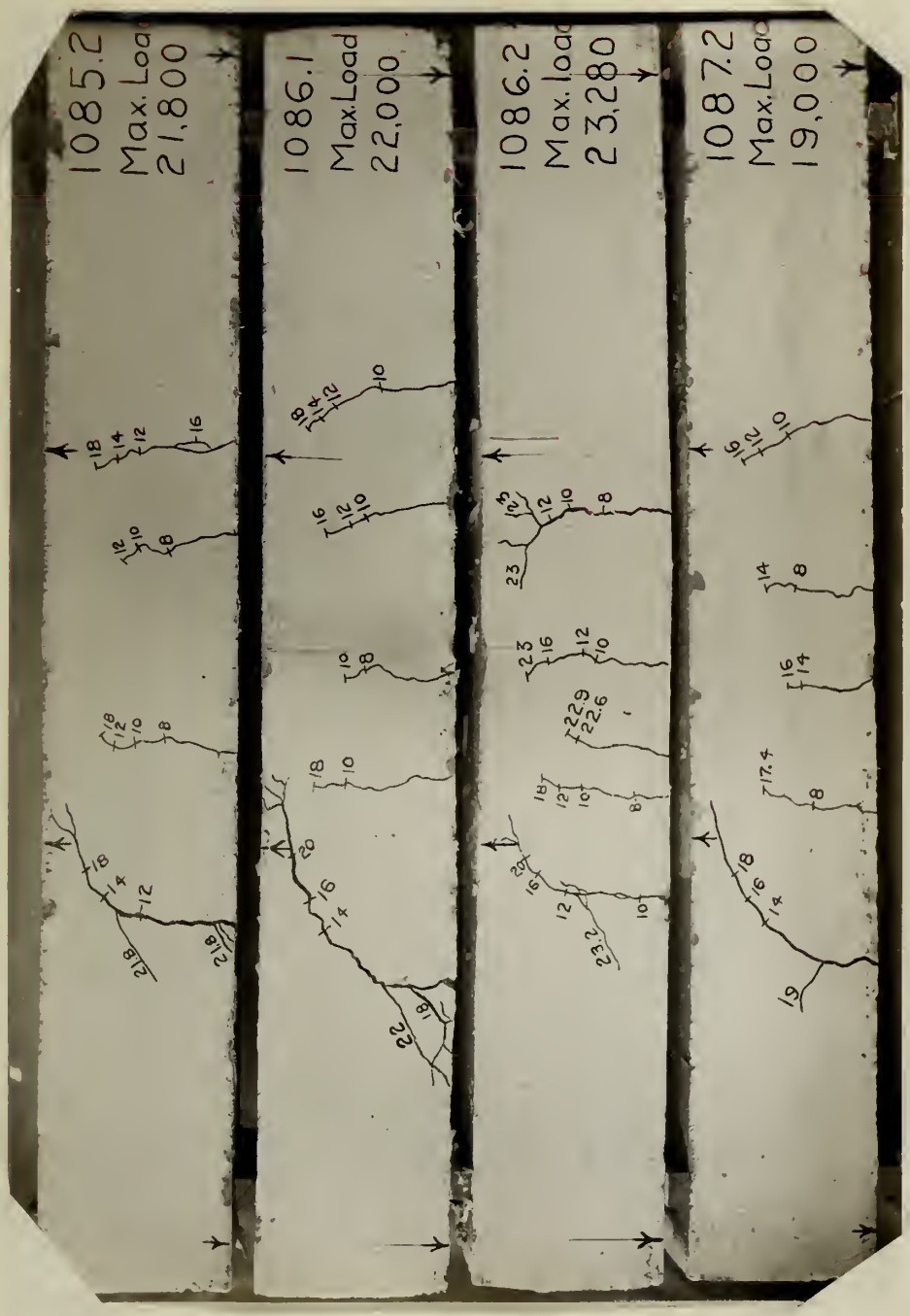


Figure 23. Reinforced Concrete Beams After Test.

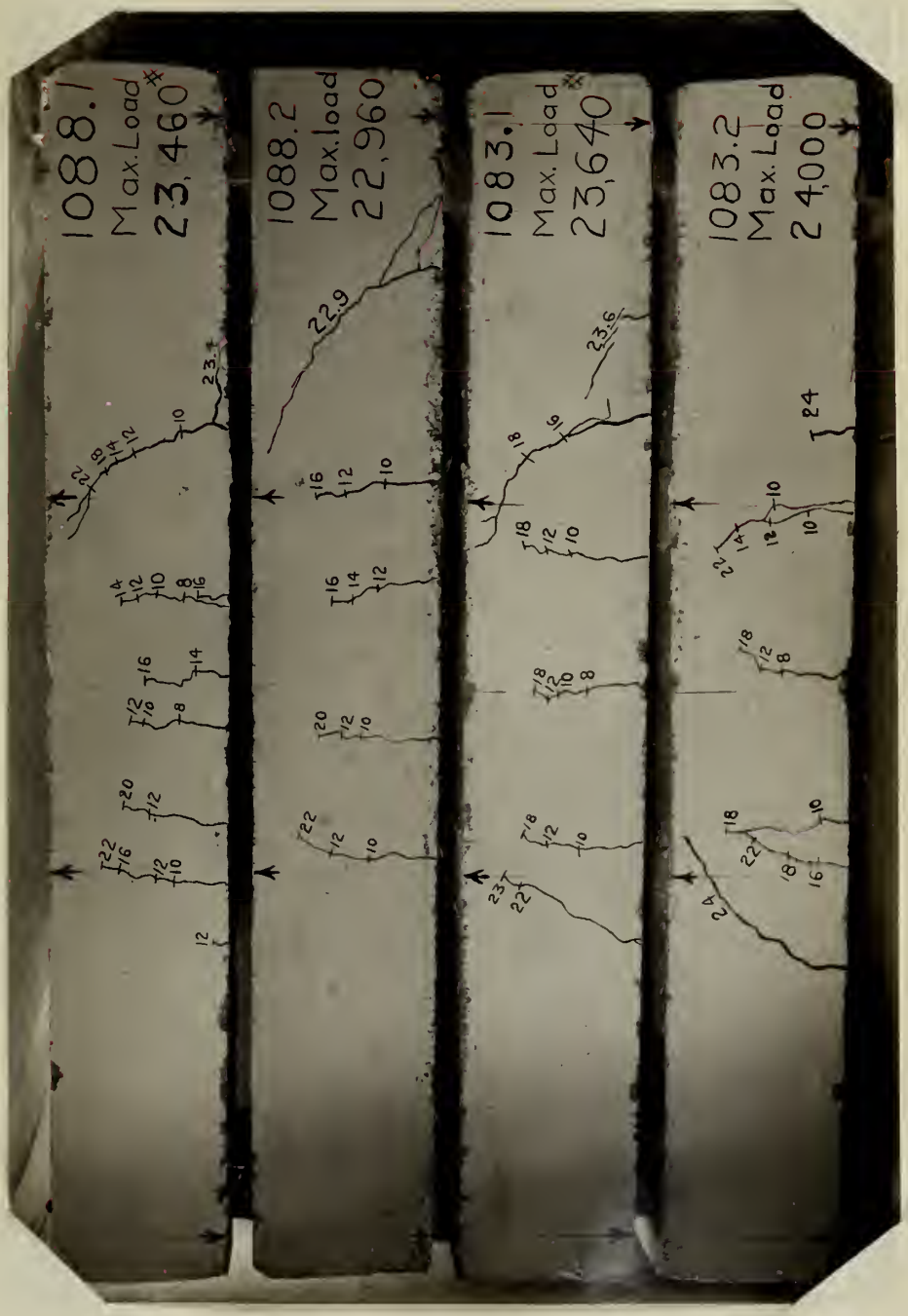


Figure 24. Reinforced Concrete Beams After Test.

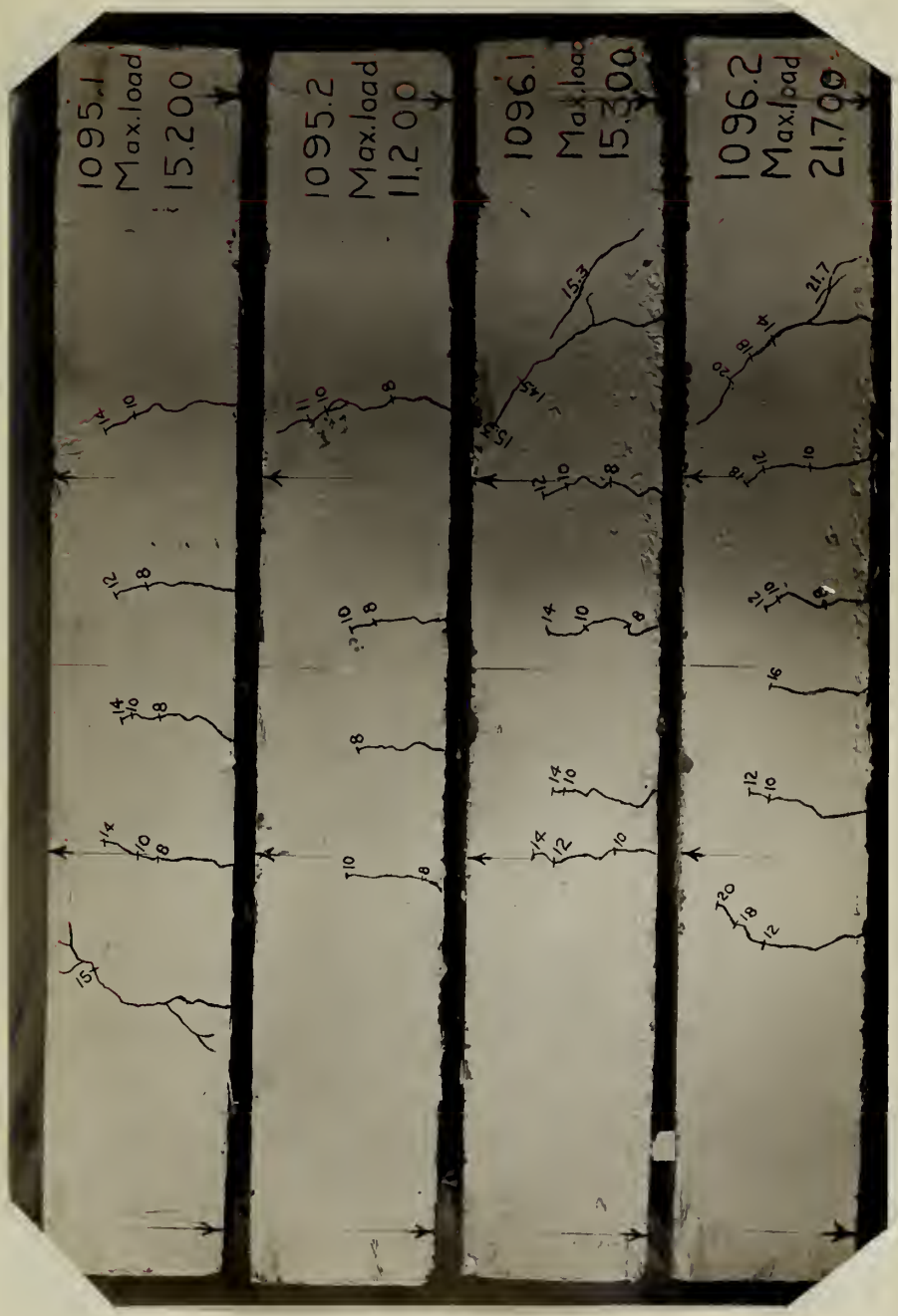


Figure 25. Reinforced Concrete Beams After Test.

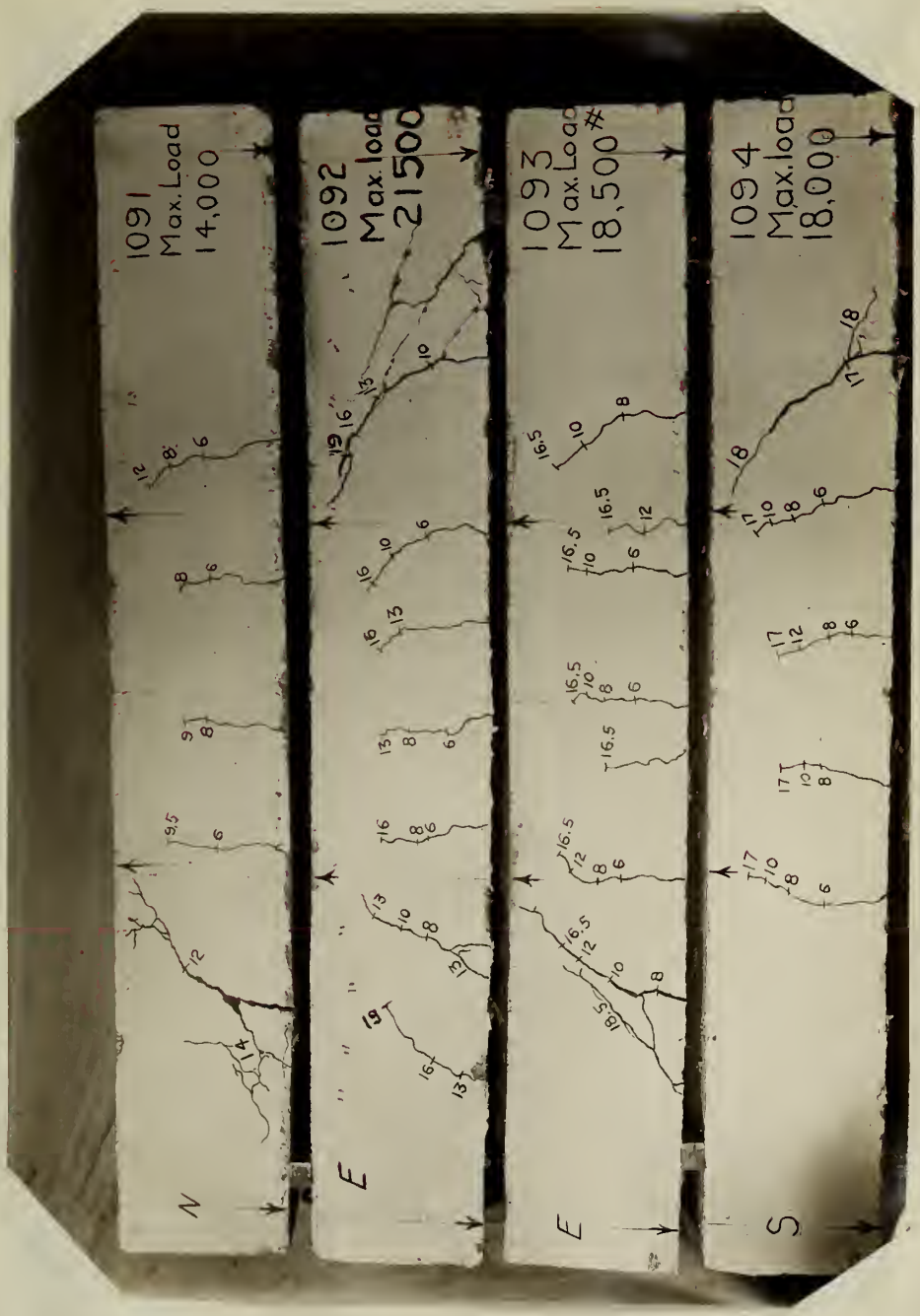


Figure 26. Reinforced Concrete Beams After Test.

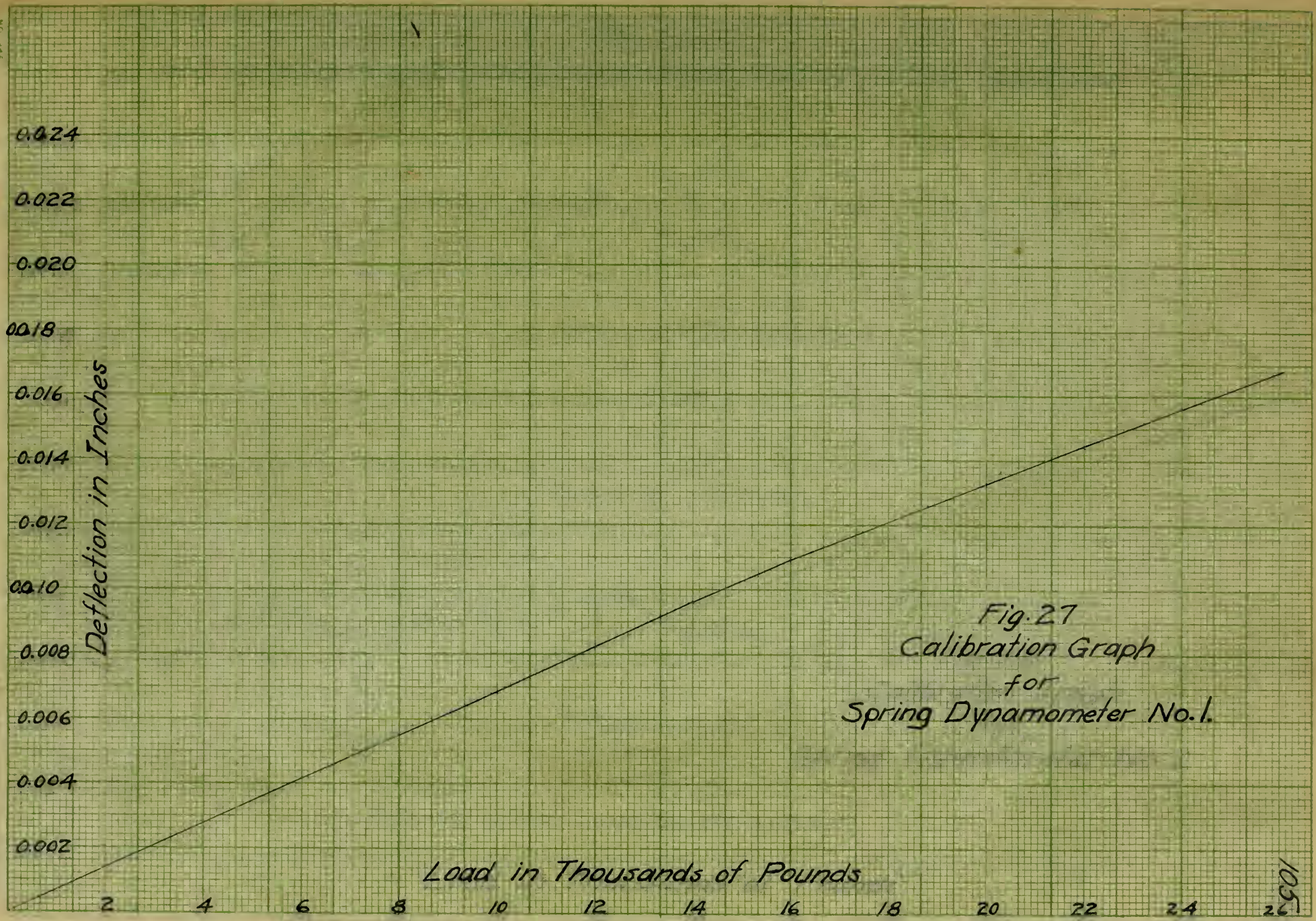


Fig. 27
Calibration Graph
for
Spring Dynamometer No. 1.

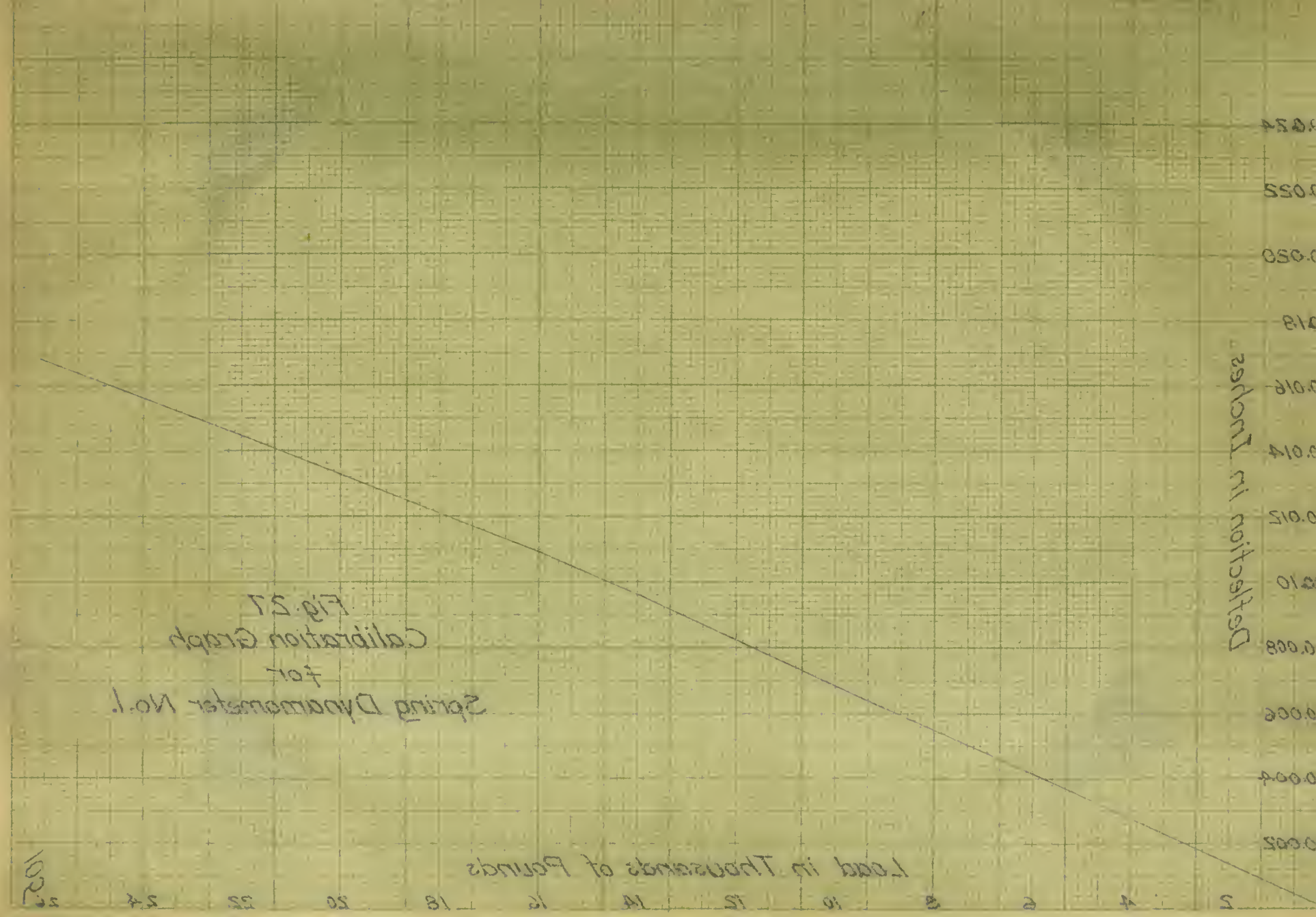


Fig. 27
Calibration Graph
for
Spring Dynamometer No. 1.

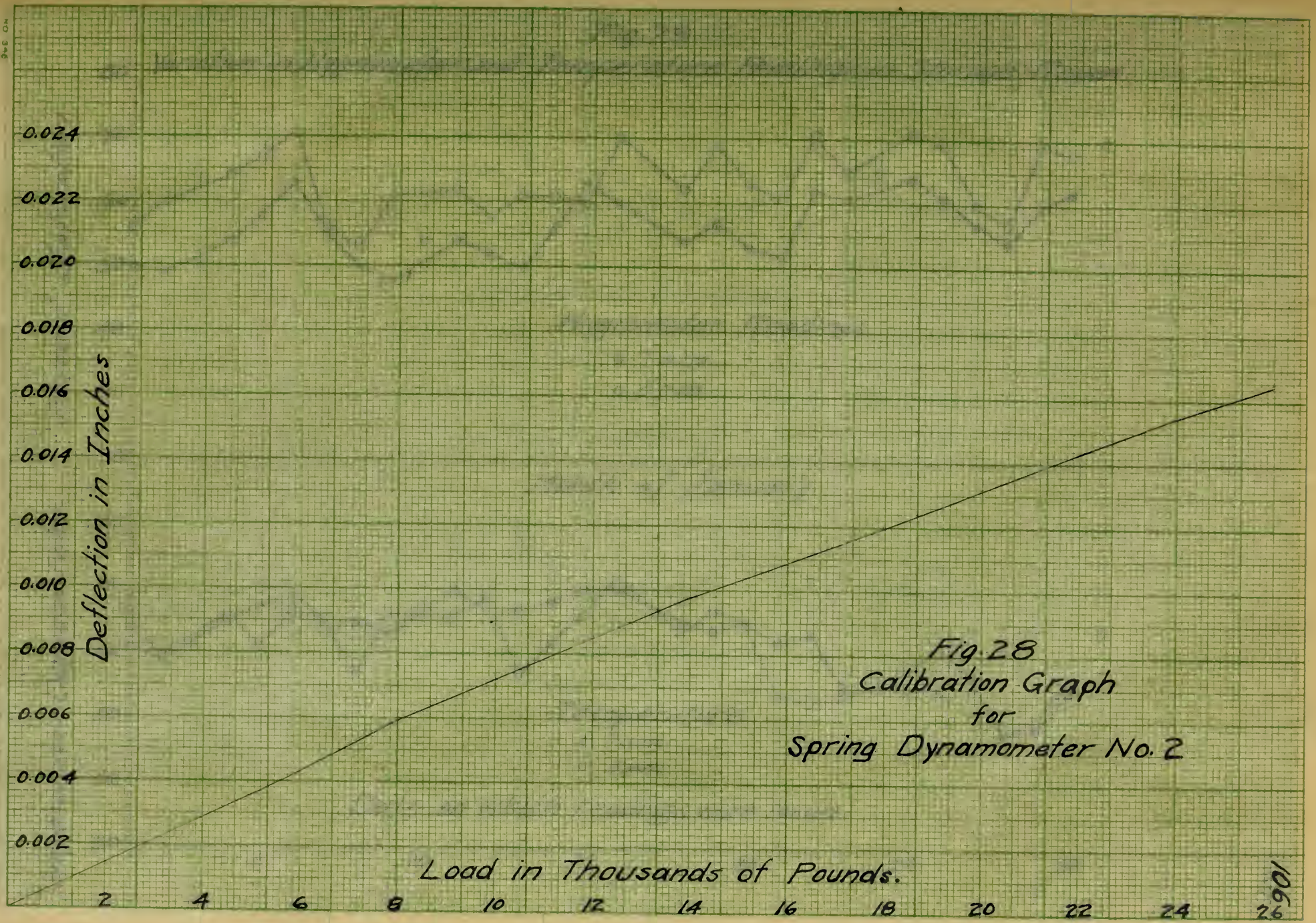
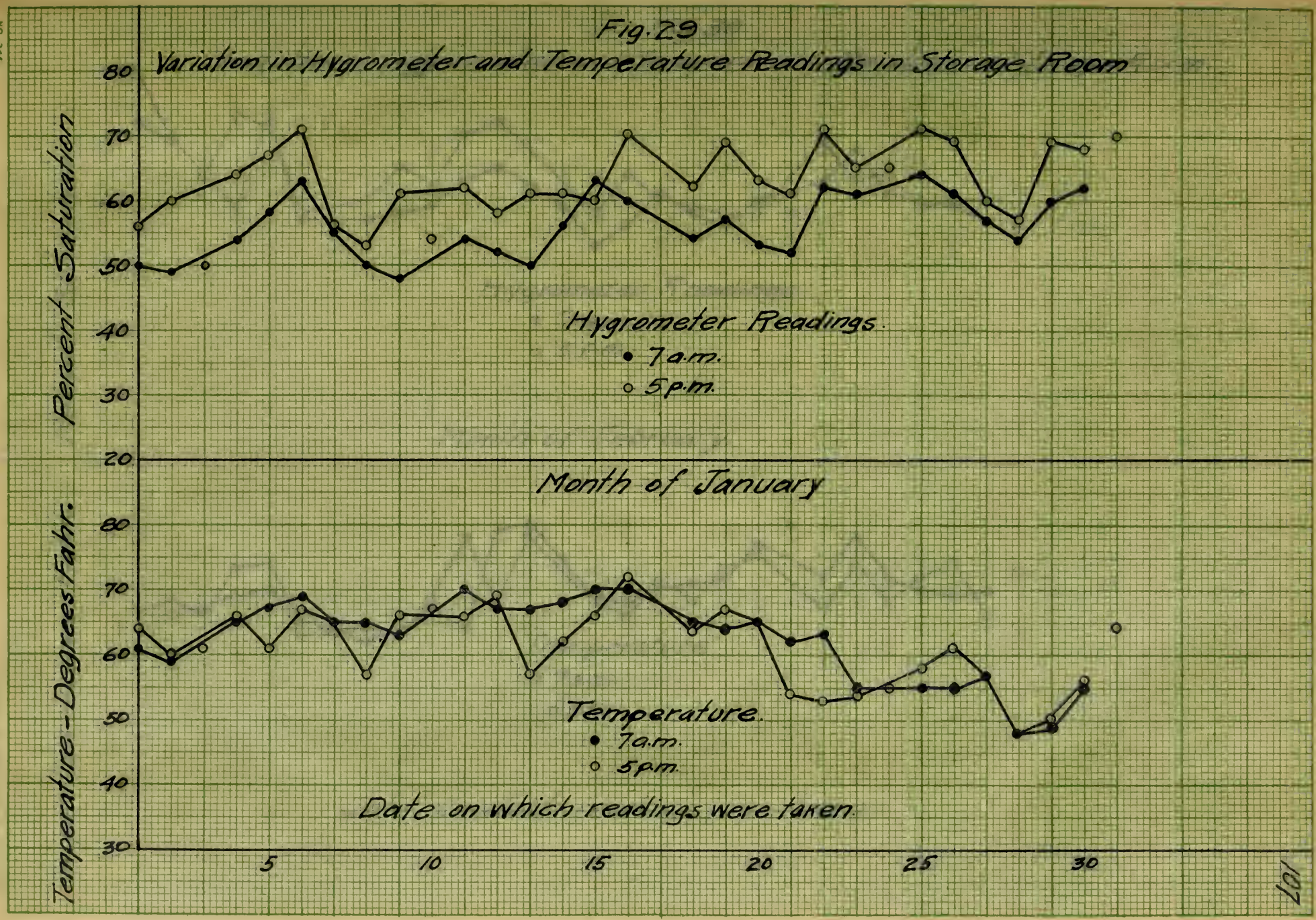


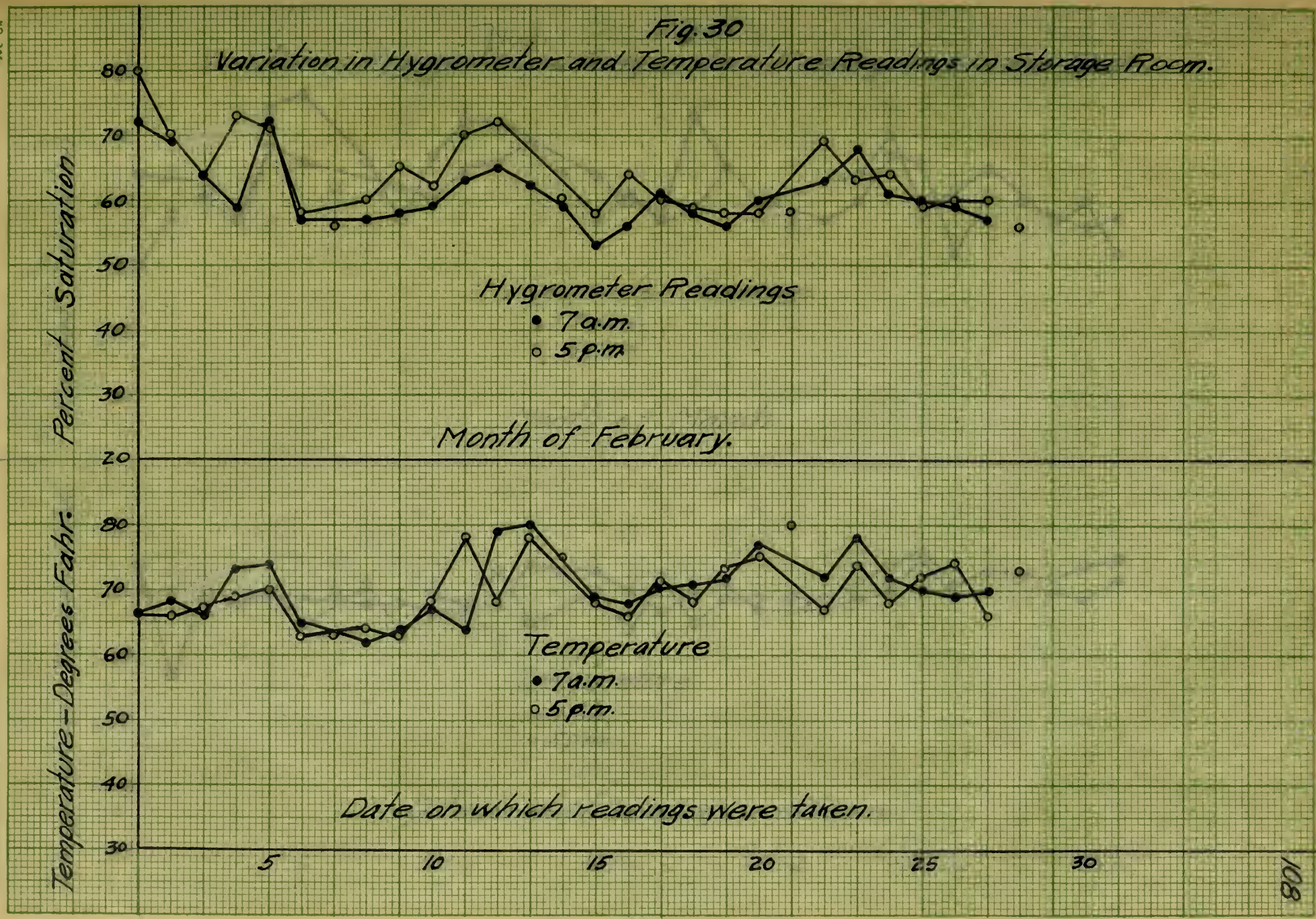
Fig. 28
Calibration Graph
for
Spring Dynamometer No. 2

Deflection in Inches
.0005
.0010
.0015
.0020
.0025
.0030
.0035
.0040
.0045
.0050
Load in Thousands of Pounds
0
2
4
6
8
10
12
14
16
18
20
22
24
26
28
30
32
34
36
38
40
42
44
46
48
50
52
54
56
58
60
Solid Dynamometer No. 5
Calibration Curve
Feb. 1, 1928

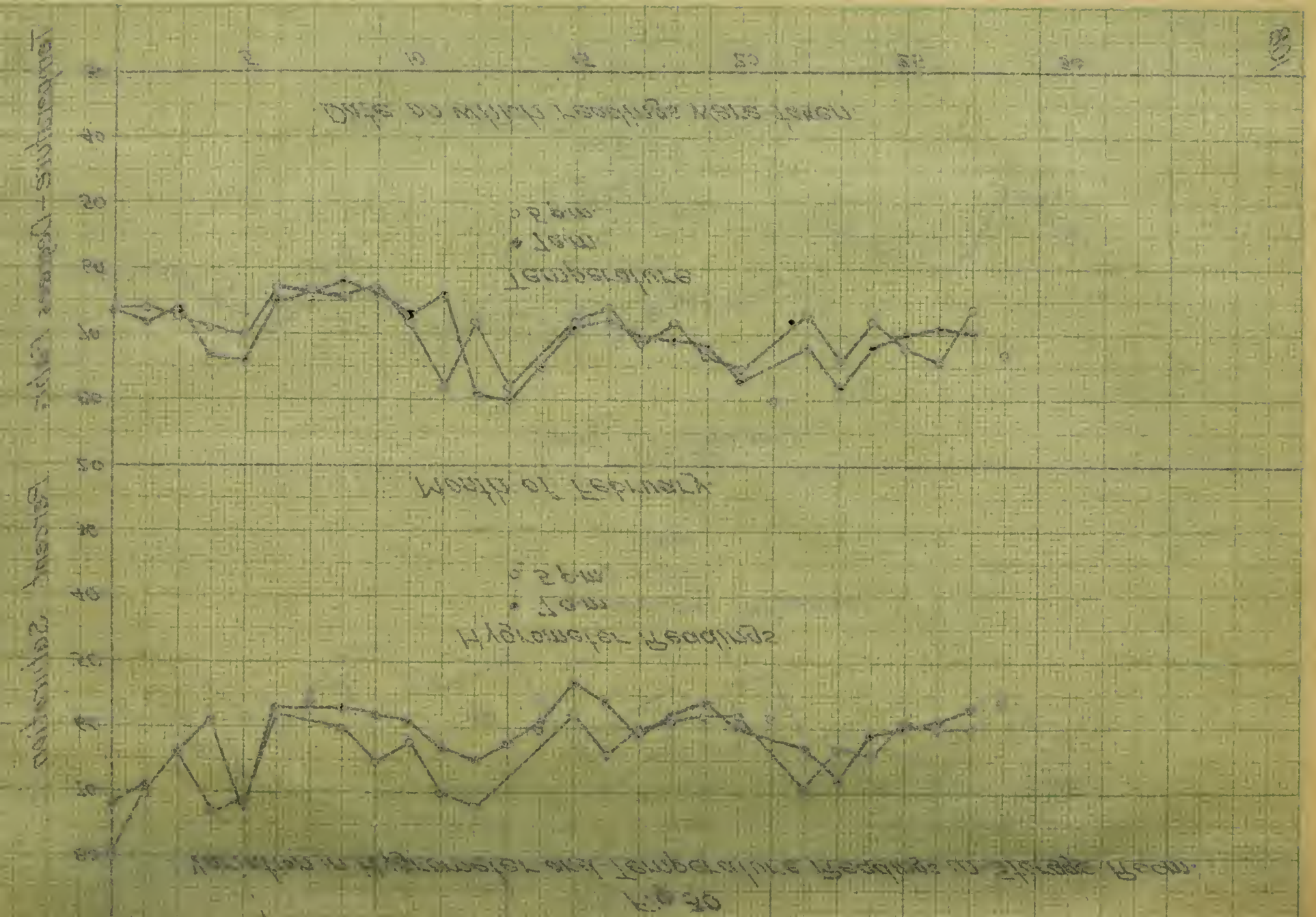


NO 346
EUGENE DIETZGEN CO CHICAGO-NEW YORK

Date of Minimum Temperature Reached
Lowest Temperature
Highest Temperature
Mean Temperature
Date of Maximum Temperature Reached
Lowest Temperature
Highest Temperature
Mean Temperature
Minimum Temperature in Degrees Fahr.
Maximum Temperature in Degrees Fahr.



NO 346
EUGENE D ETZBEN CO CHICAGO-NEW YORK



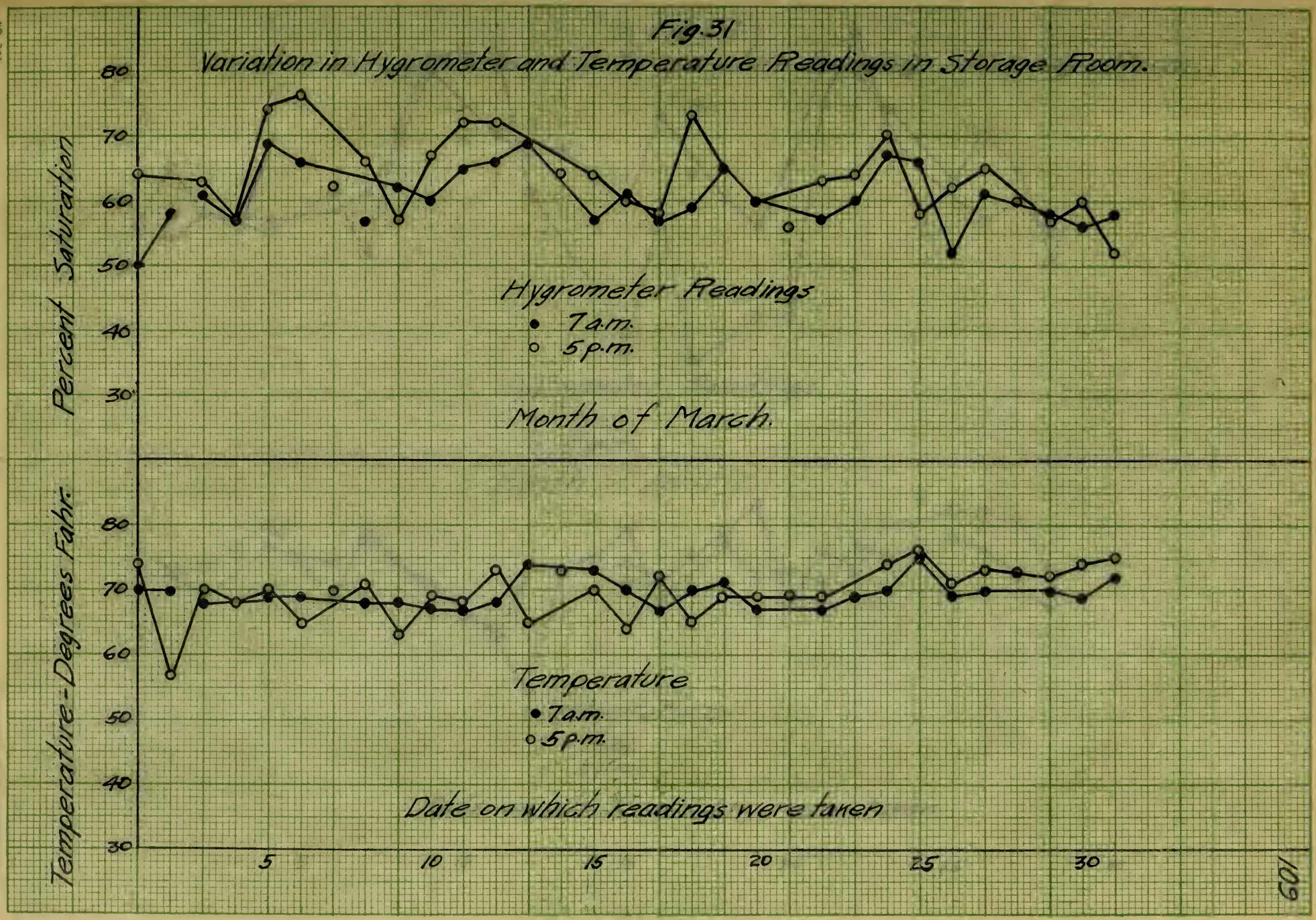


Fig. 31
Variation in Hygrometer and Temperature Readings in Storage Room.
Percent Saturation
80
70
60
50
40
30
Hygrometer Readings
• 7 a.m.
○ 5 p.m.
Month of March.
Temperature - Degrees Fahr.
80
70
60
50
40
30
Temperature
• 7 a.m.
○ 5 p.m.
Date on which readings were taken
5
10
15
20
25
30

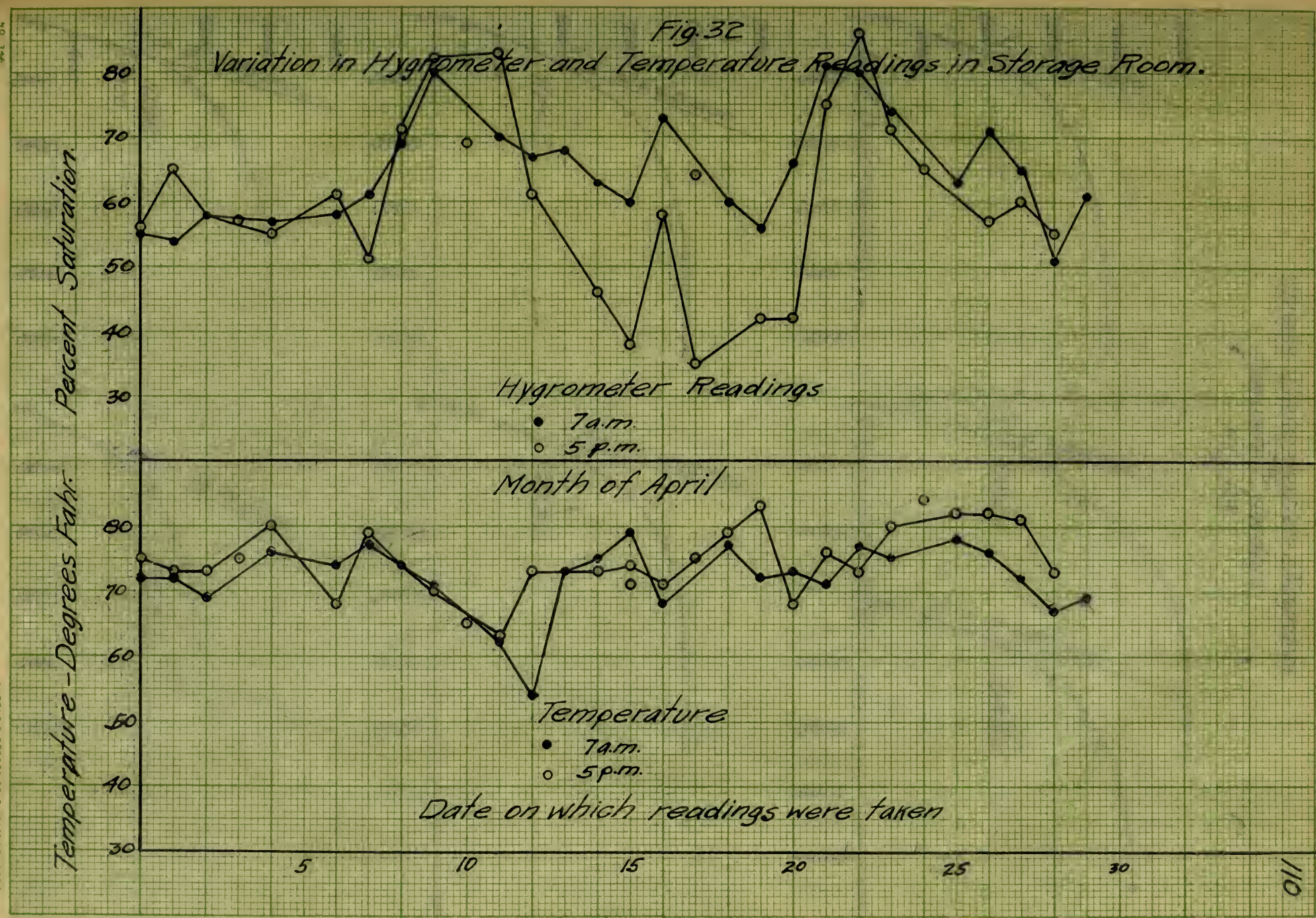
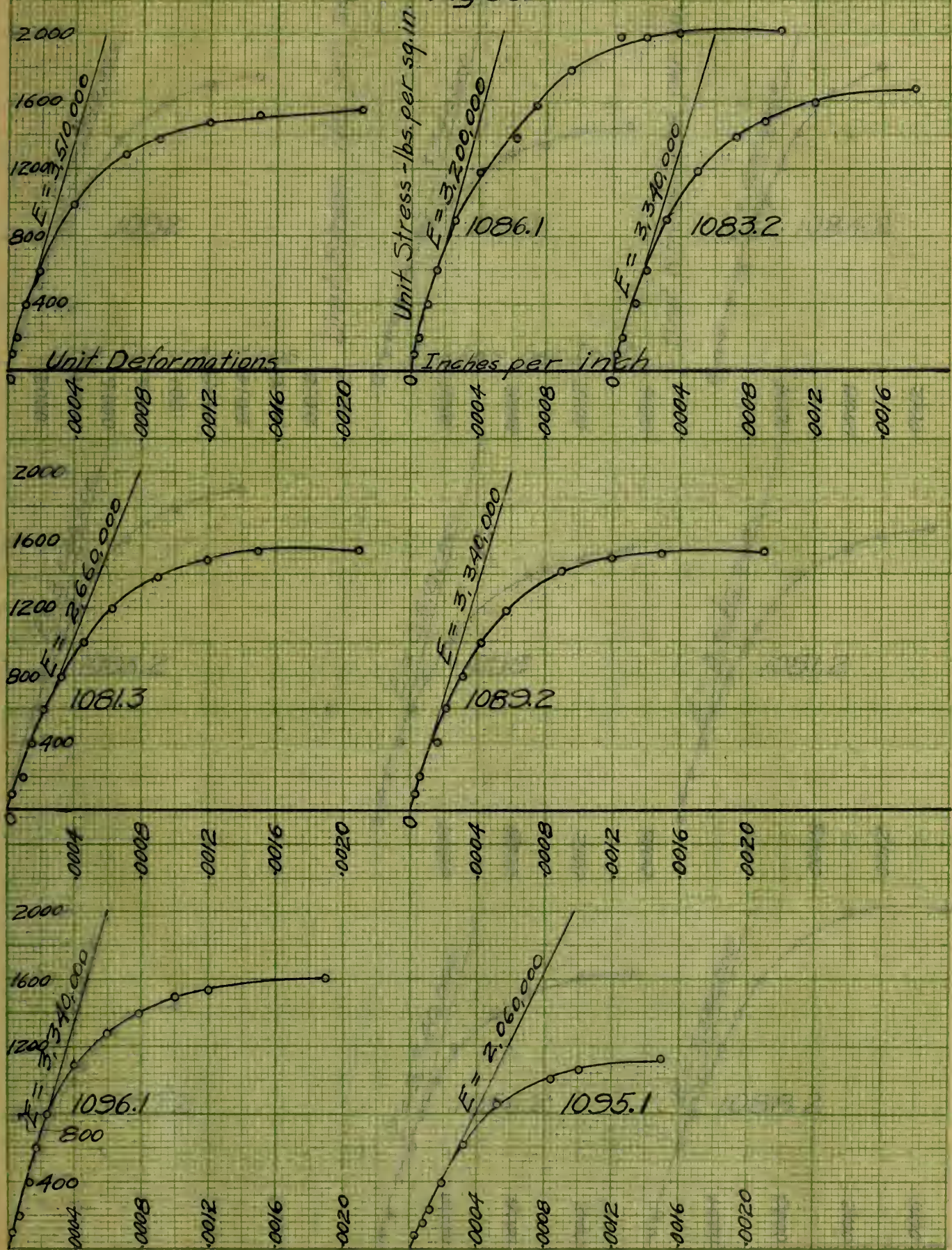


Fig. 32
Variation in Hygrometer and Temperature Readings in Storage Room.
Percent Saturation
80
70
60
50
40
30
Hygrometer Readings
7 a.m.
5 p.m.
Month of April
Temperature - Degrees Fahr.
80
70
60
50
40
30
Temperature
7 a.m.
5 p.m.
Date on which readings were taken
5
10
15
20
25
30

Temperature - Degrees Fahr.
Precip. Inches
Daily Means of Hourly Observations
Daily Means of Hourly Observations
Fig. 35

Stress-Deformation Diagrams for Concrete Cylinders

Fig. 33



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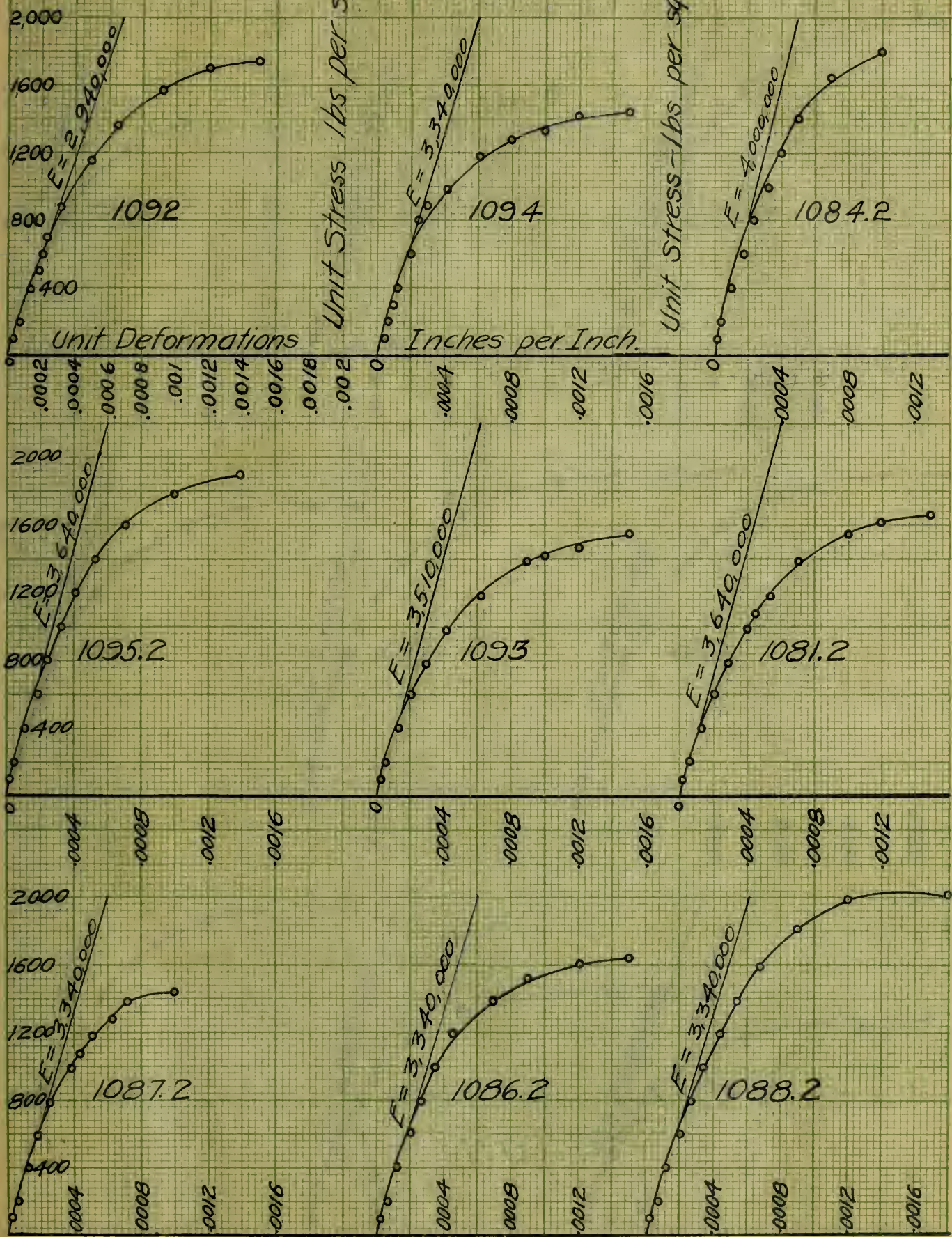
Stress-Deformation Diagrams
for
Concrete Cylinders
Fig. 33

Stress-Deformation Diagrams for Concrete Cylinders

Fig. 34



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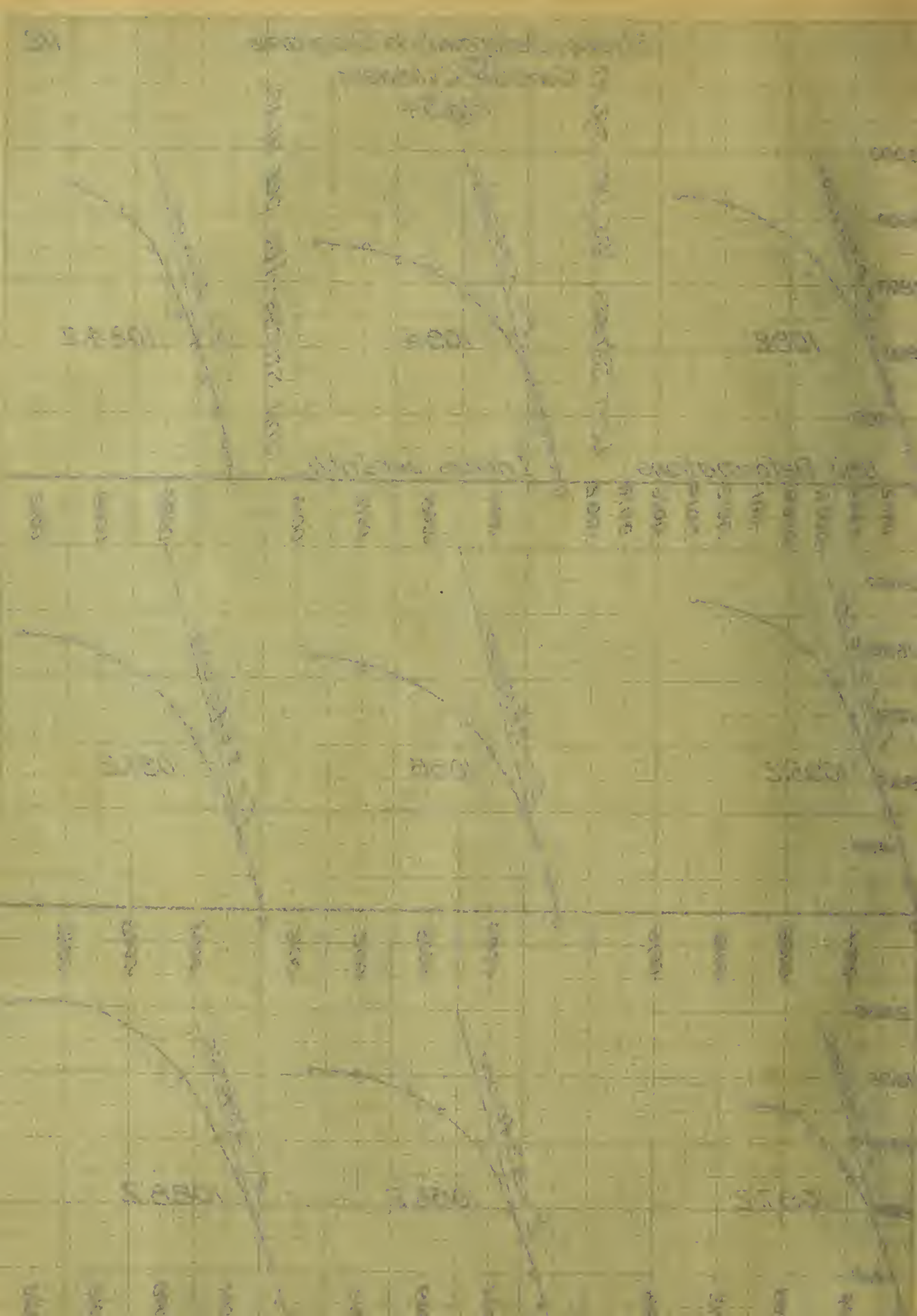
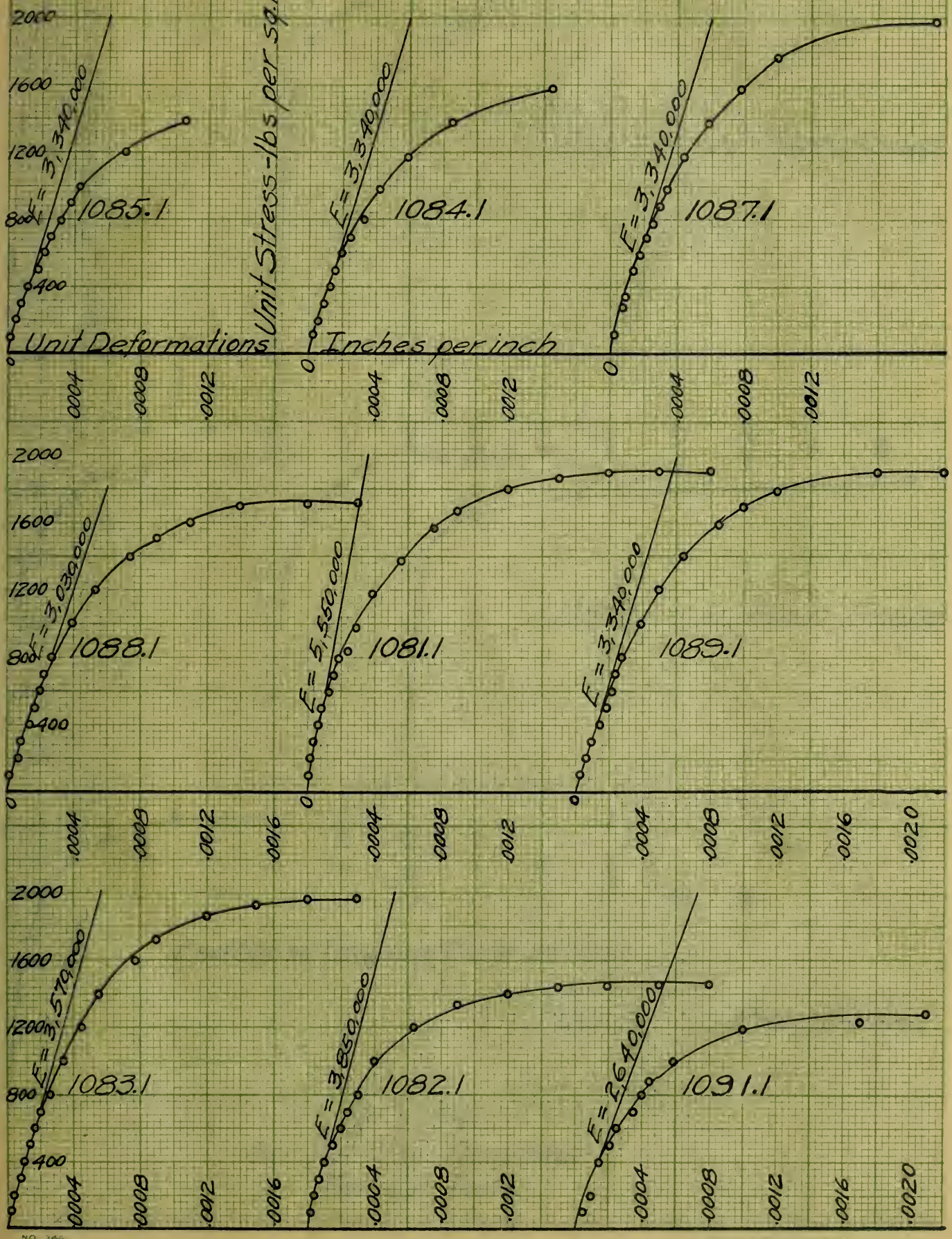
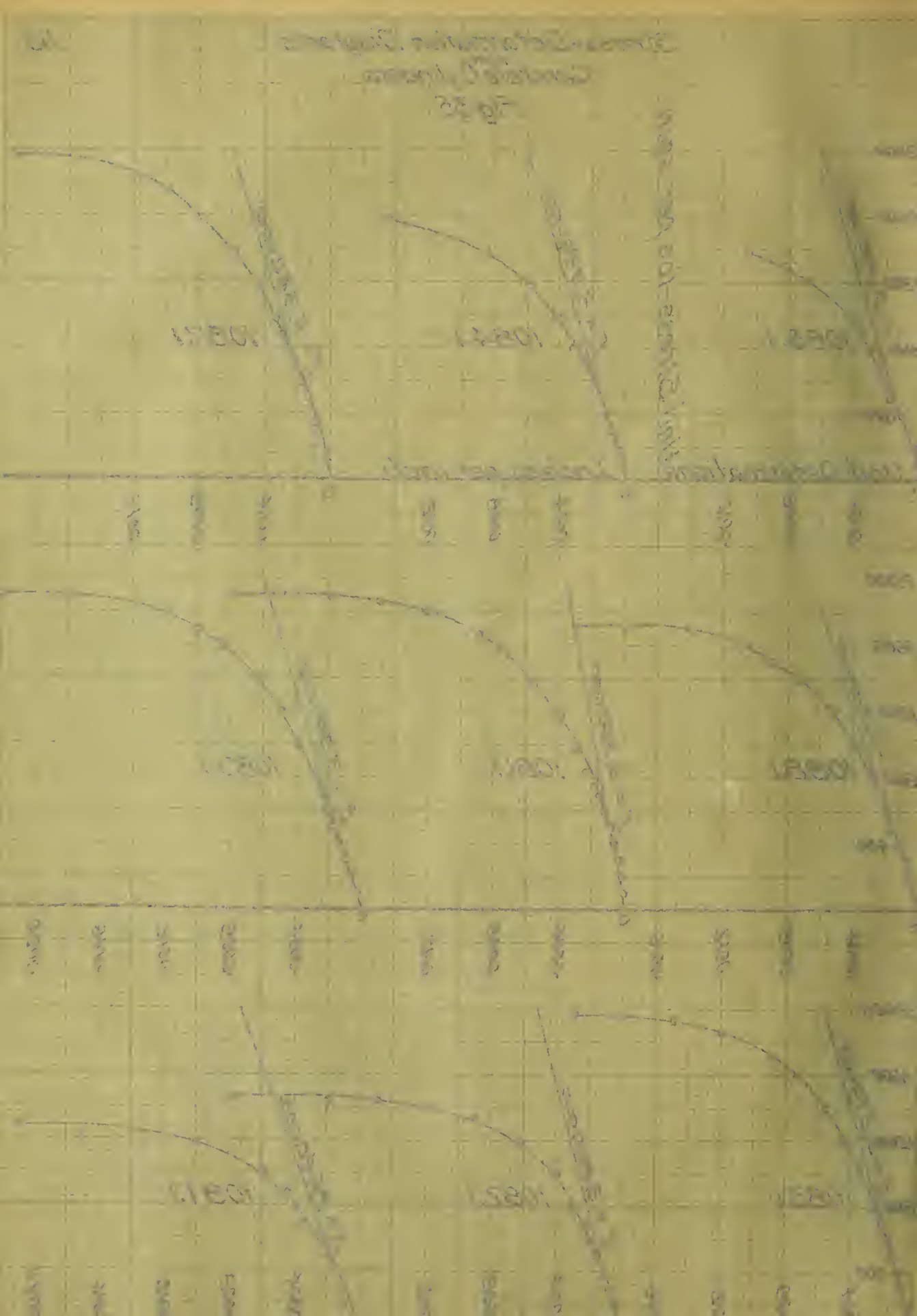


Stress-Deformation Diagrams for Concrete Cylinders

Fig. 35





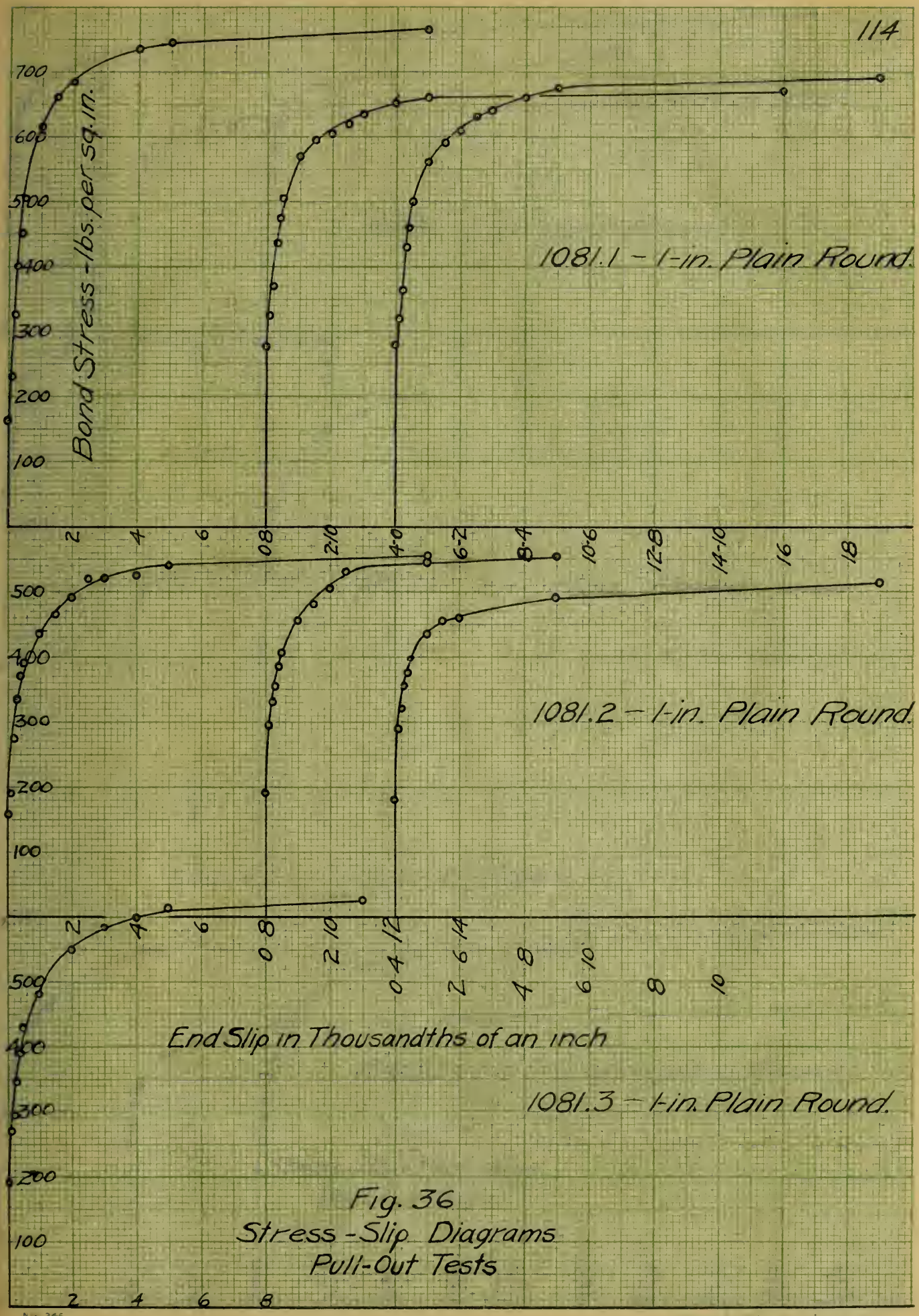


Fig. 36
Stress - Slip Diagrams
Pull-Out Tests

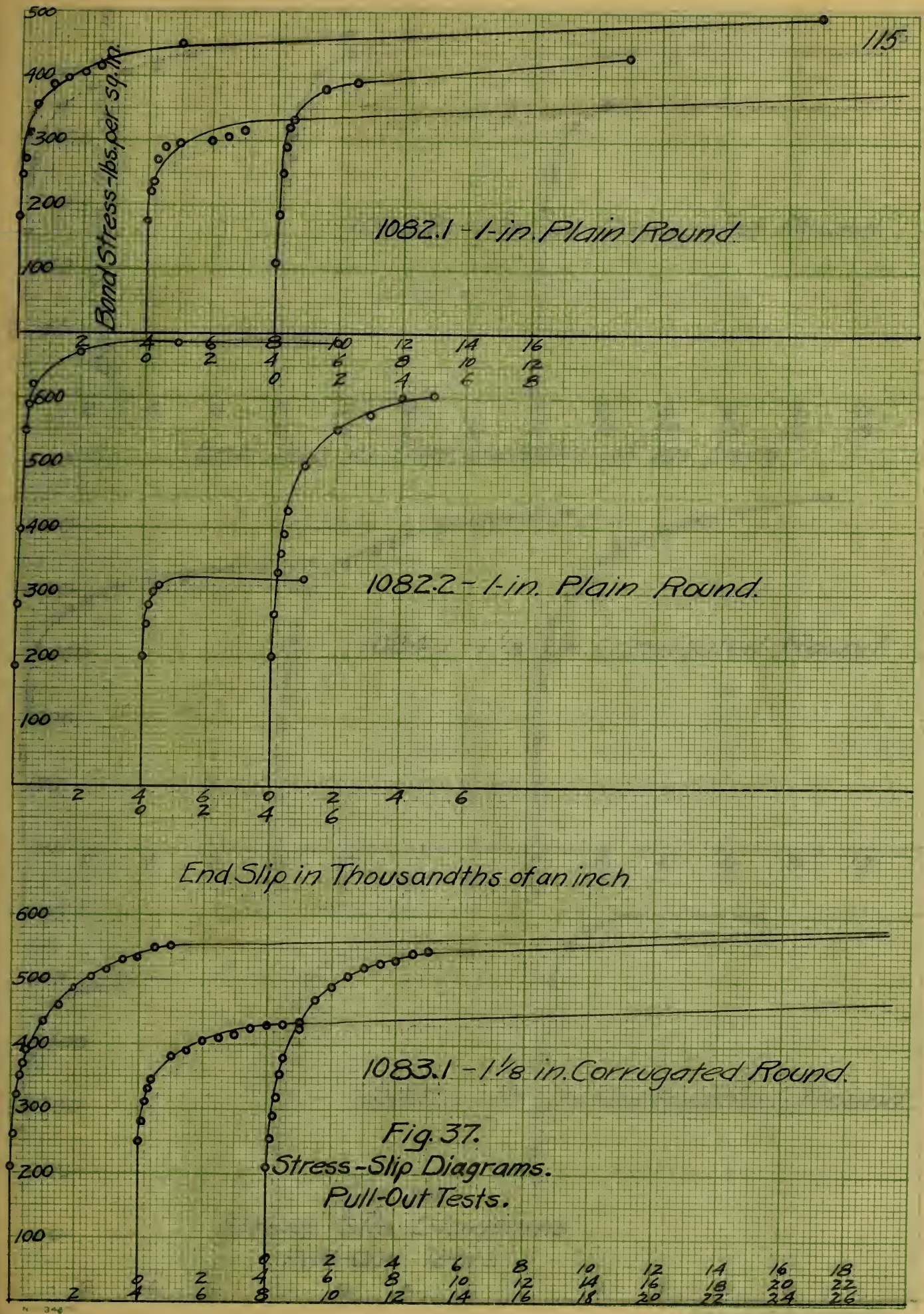


Fig. 37.
Stress-Slip Diagrams.
Pull-Out Tests.

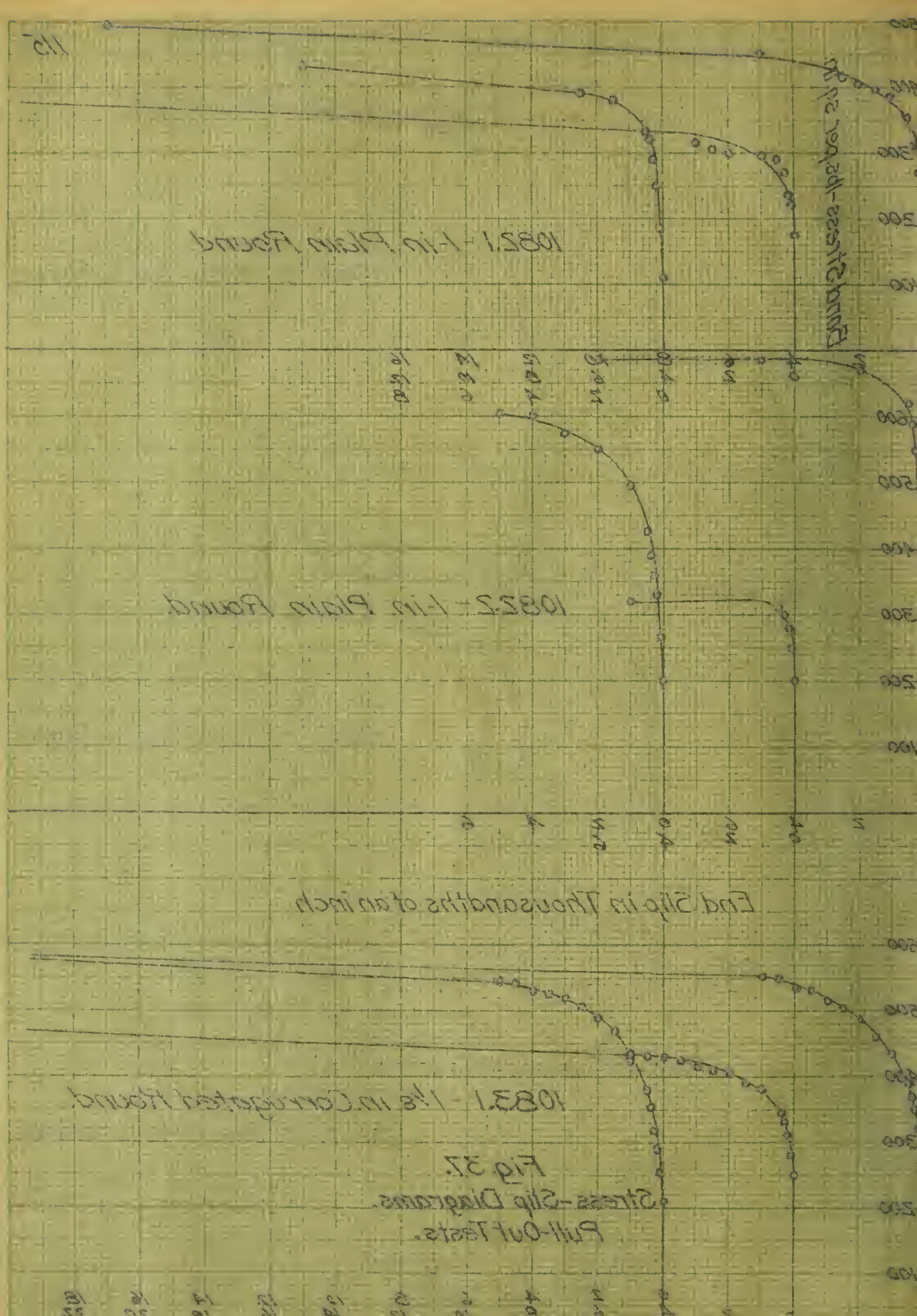


Fig 32.
Stress-Slip Diagrams.
Pull-Out Tests.

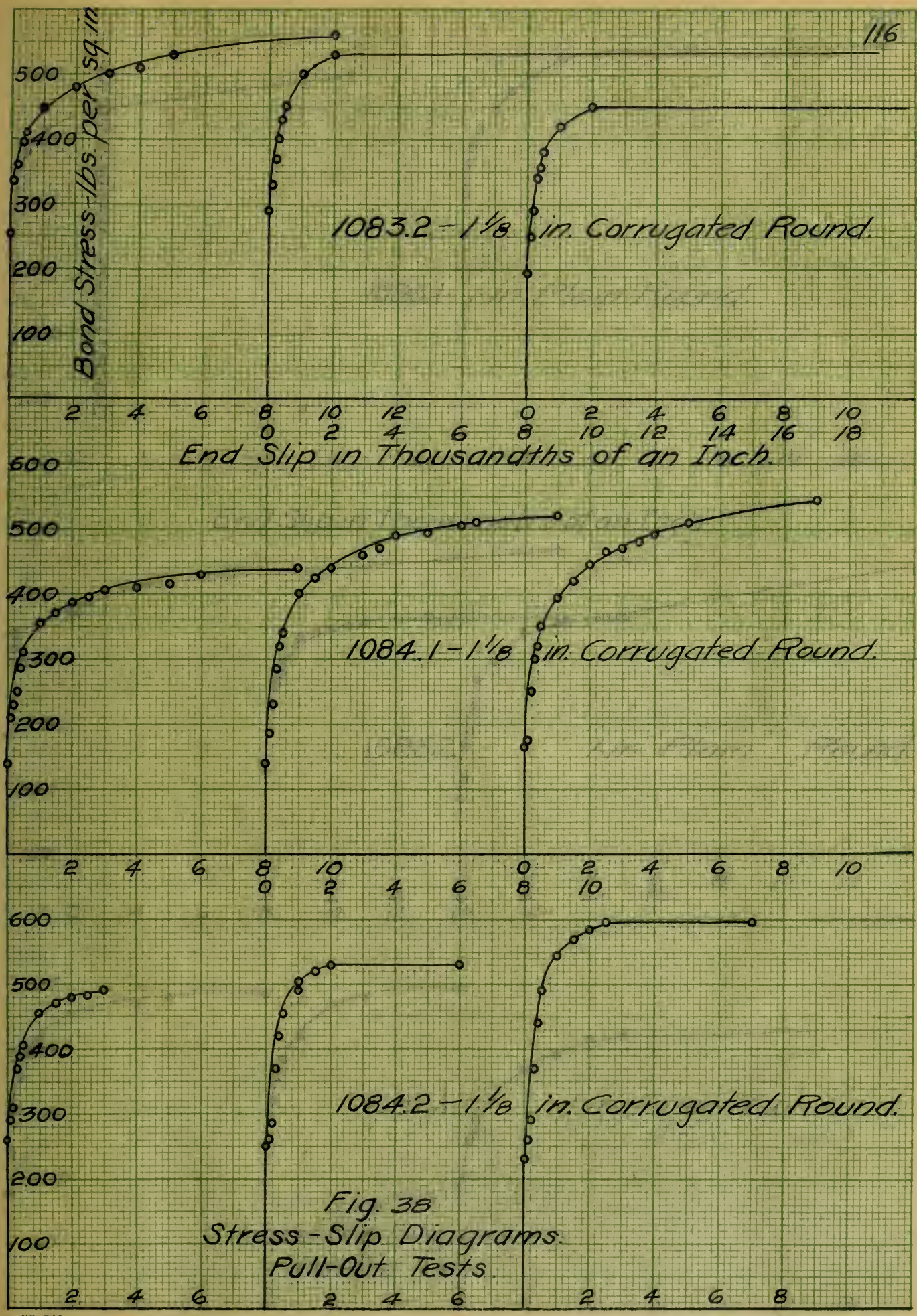


Fig. 38
Stress-Slip Diagrams.
Pull-Out Tests.

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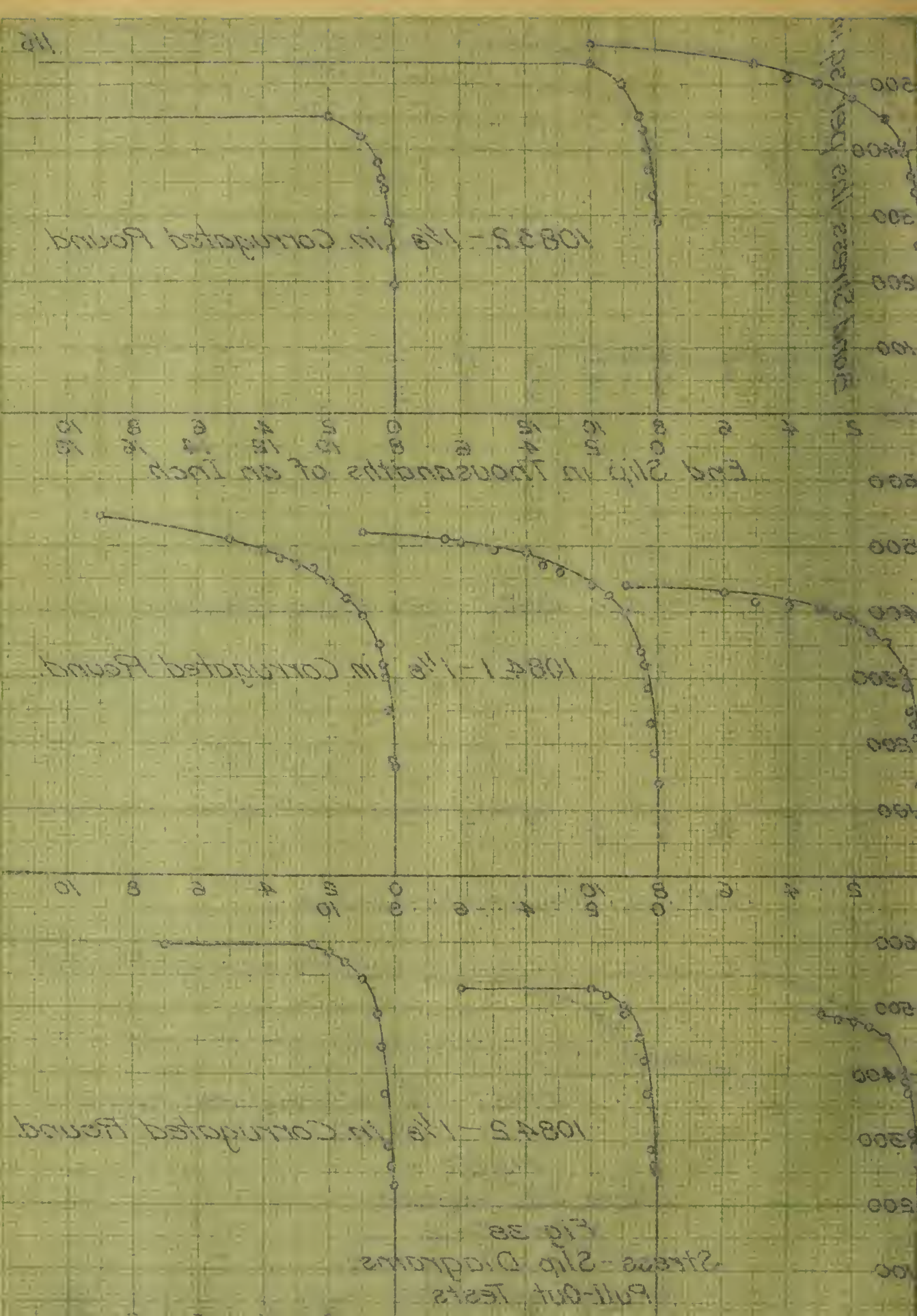

Fig 38
Stress - Slip Diagrams
Pull-Out Tests

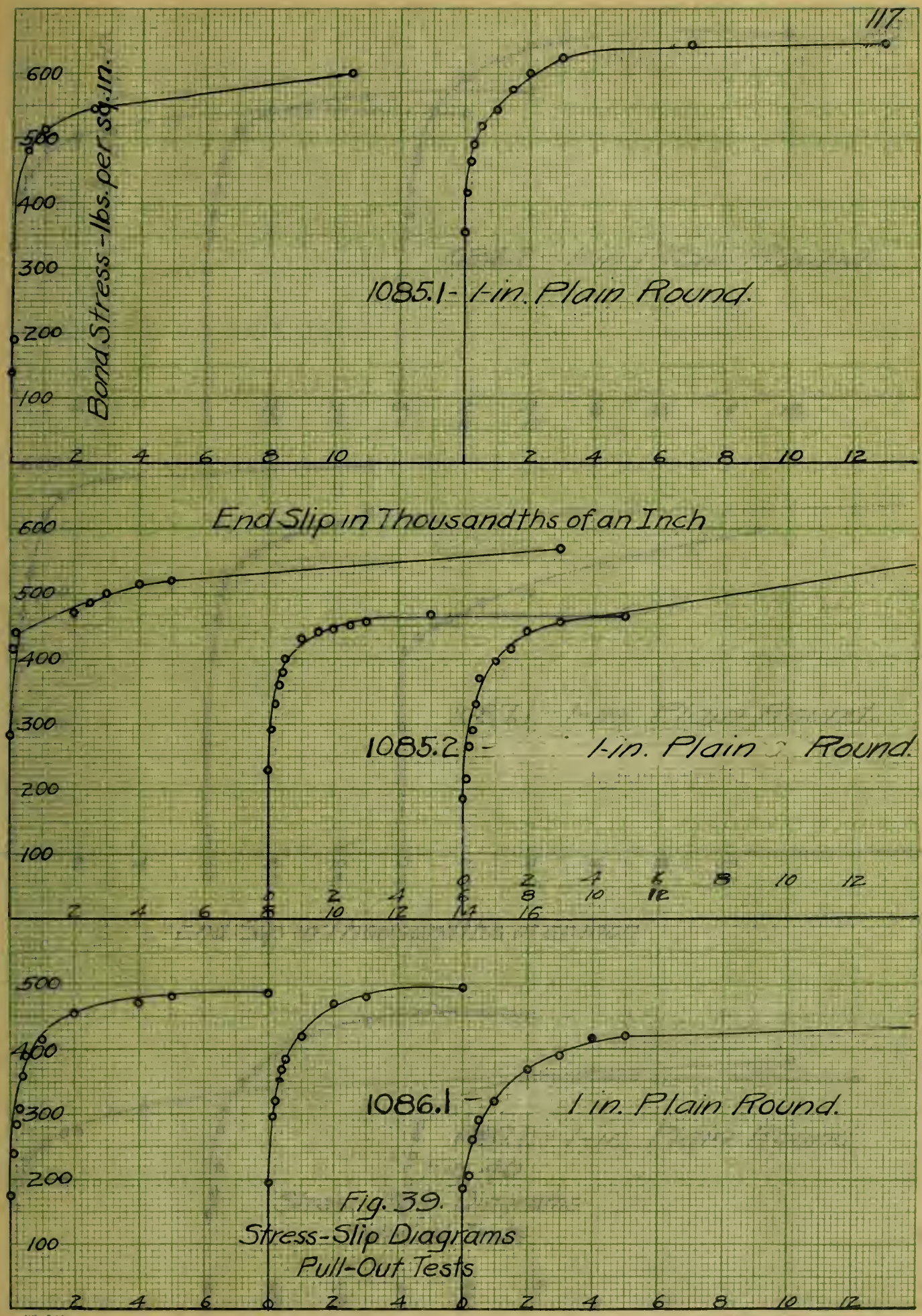

Fig. 39.
Stress-Slip Diagrams
Pull-Out Tests

NO 346
EUGENE DIETZGEN CO. CHICAGO-NEW YORK

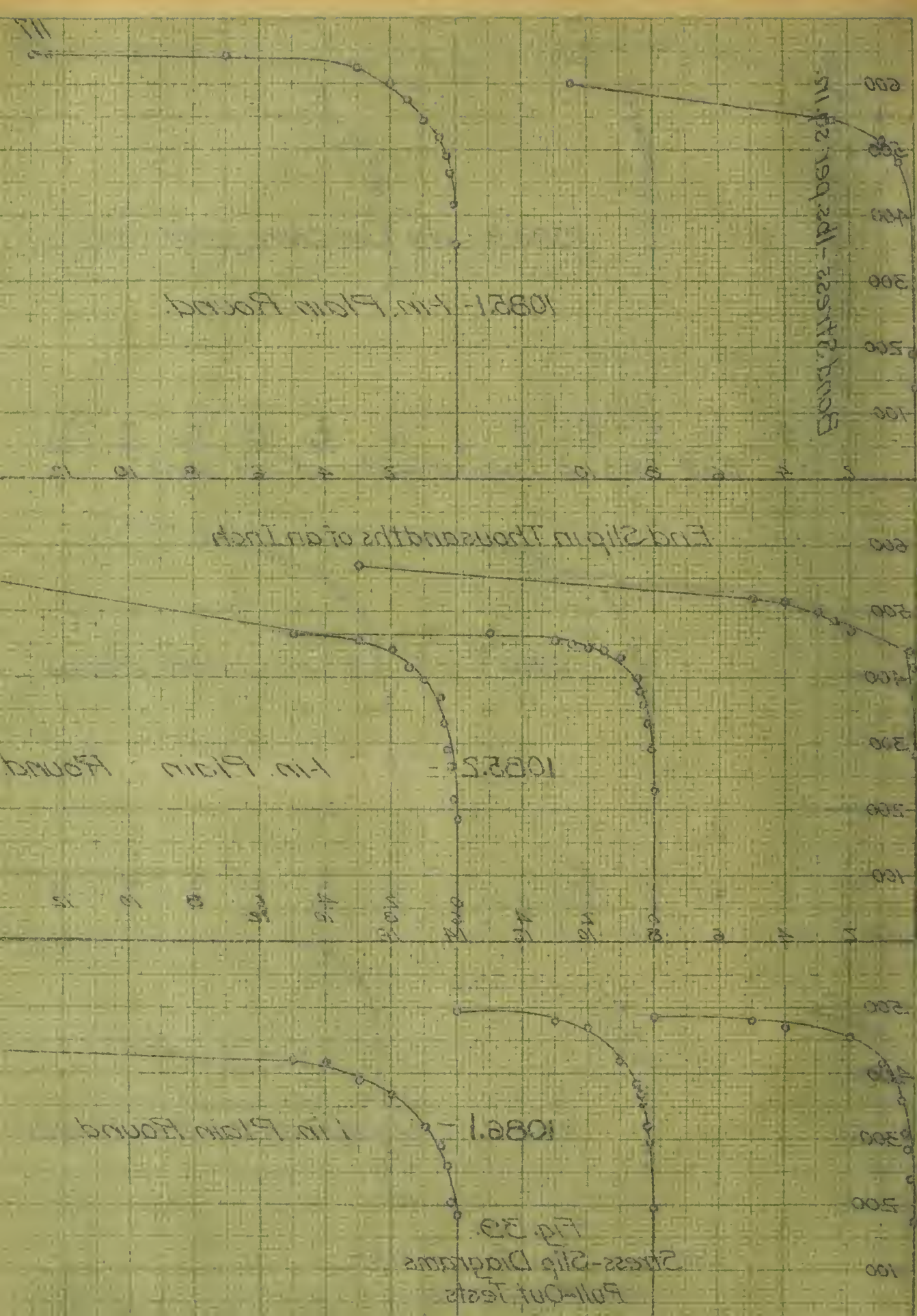

Fig. 39.
Stress-Slip Diagrams
Pull-Out Tests

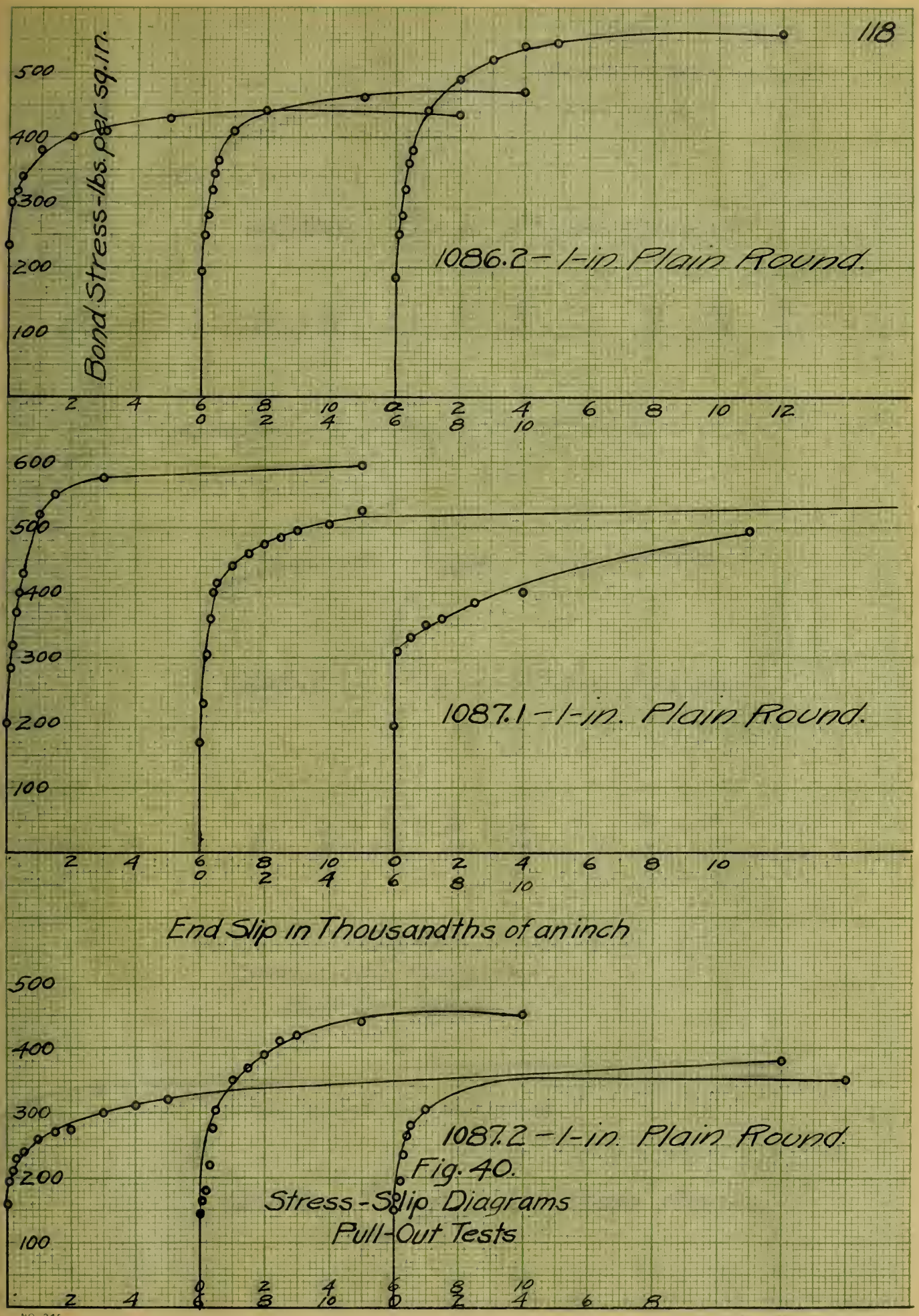

Fig. 40.
Stress-Slip Diagrams
Pull-Out Tests

EUGENE DIETZGEN CO. CHICAGO-NEW YORK

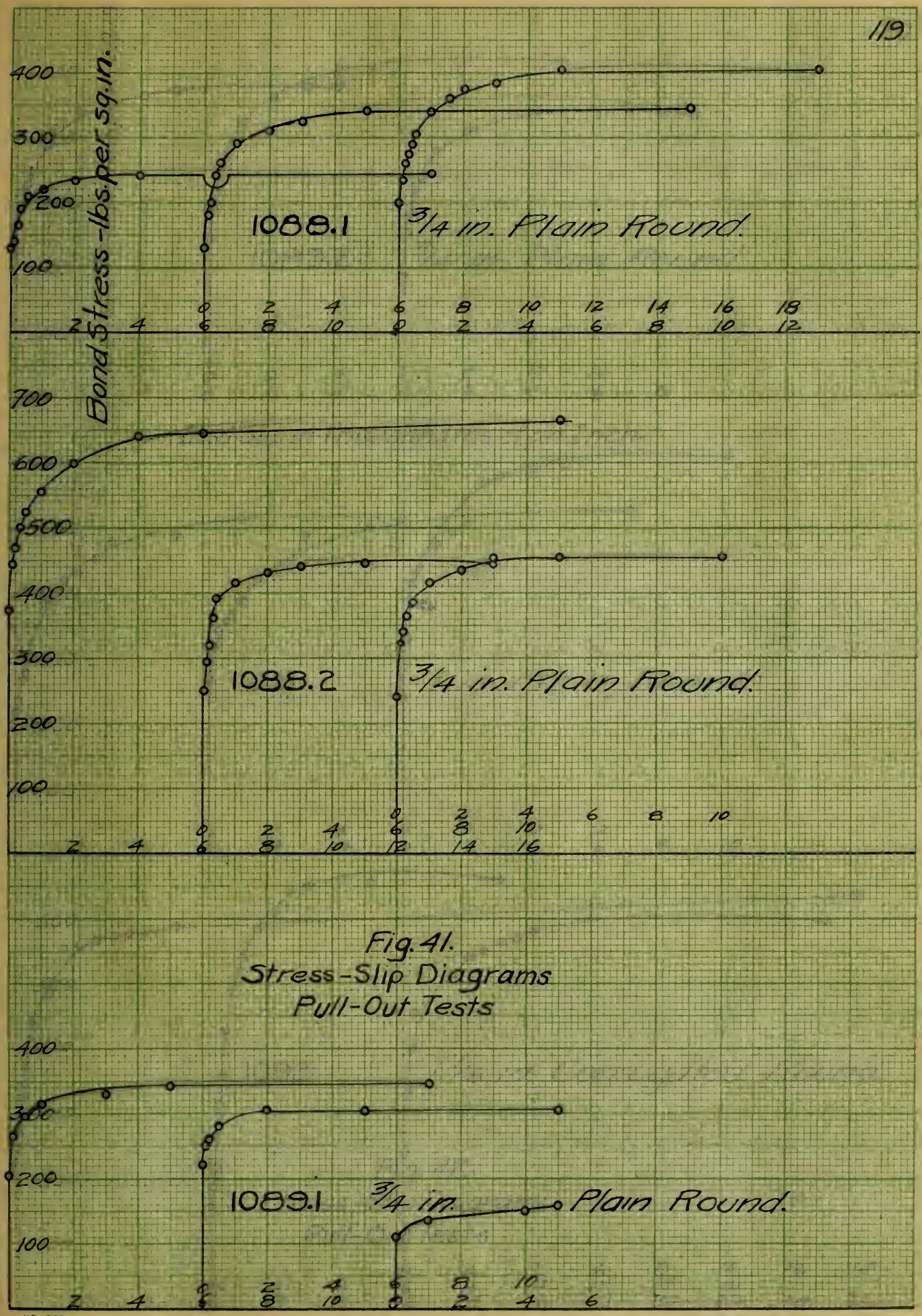

Fig. 41.
Stress-Slip Diagrams
Pull-Out Tests

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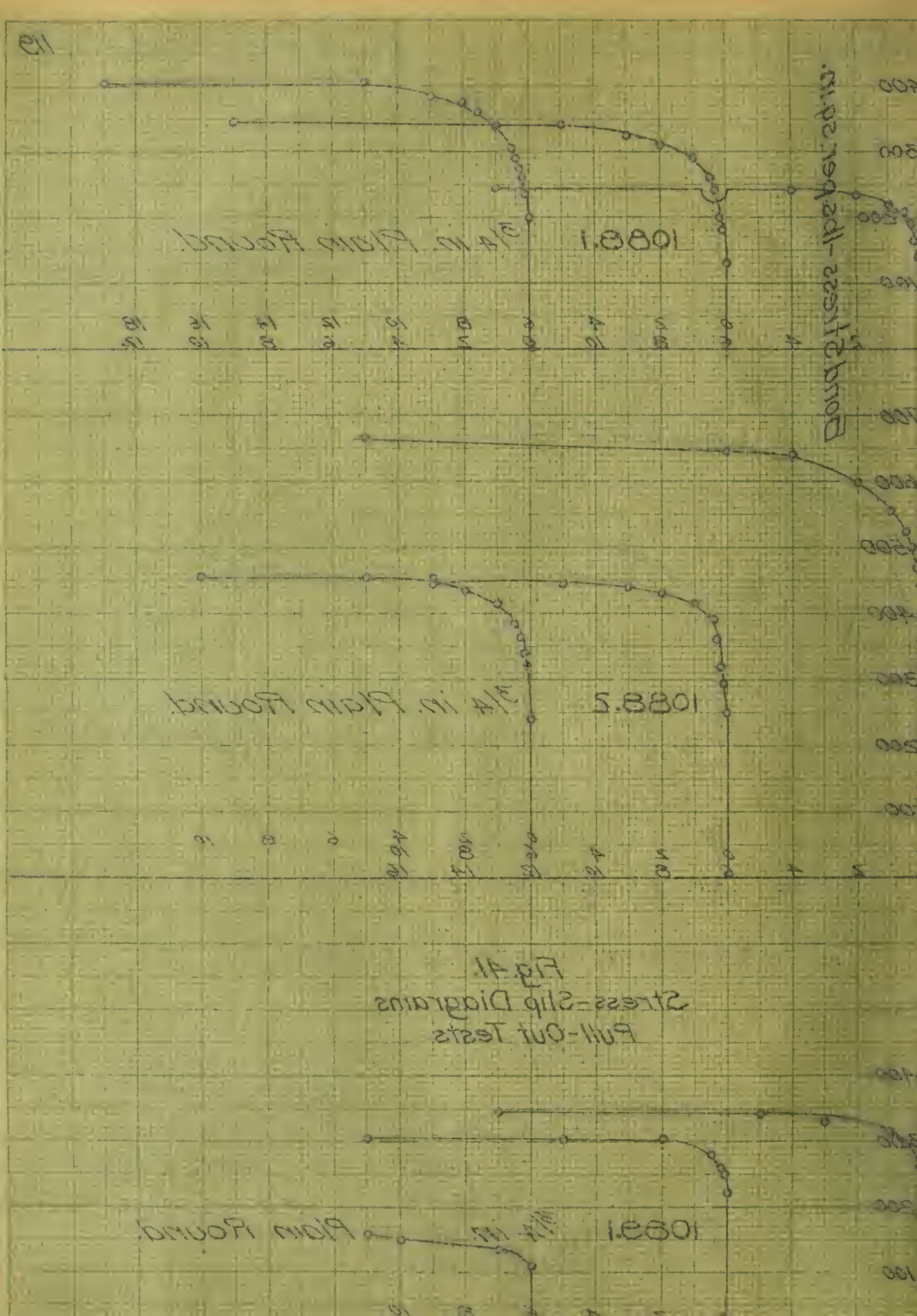

Fig. 41
Stress-Slip Diagrams
Pull-Out Tests

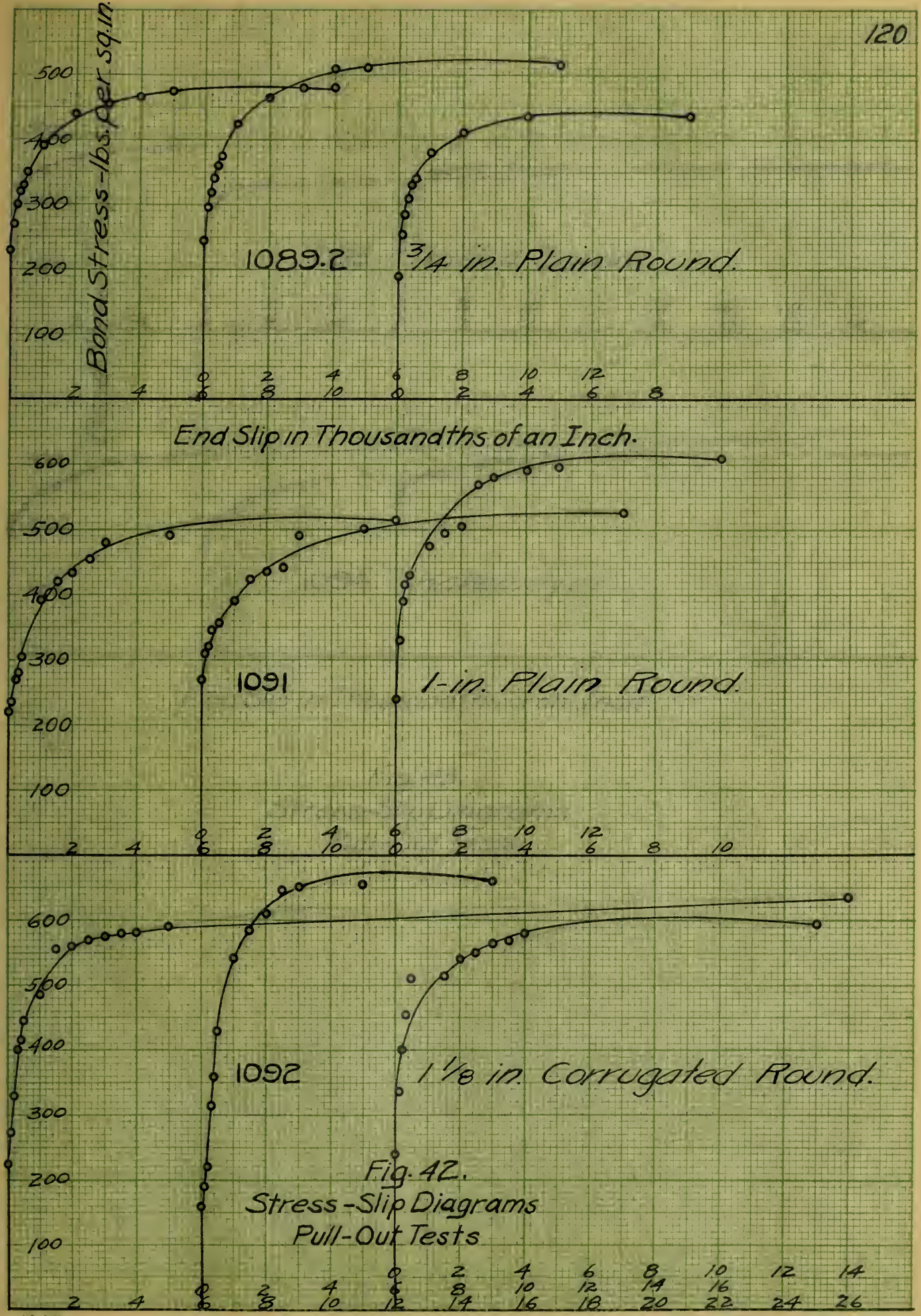

Fig. 42.
Stress-Slip Diagrams
Pull-Out Tests

EUGENE DIETZGEN CO. CHICAGO-NEW YORK

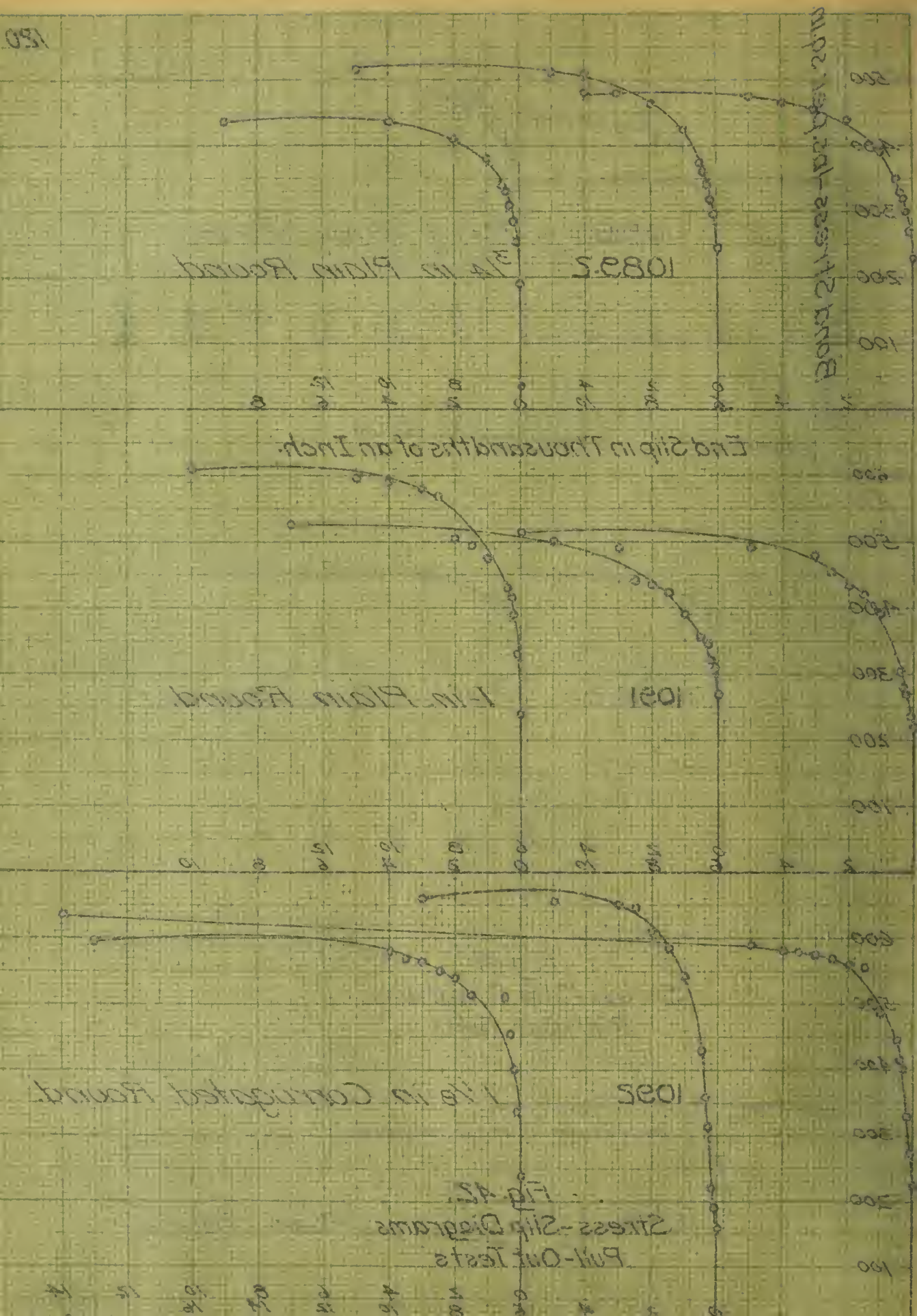

Fig. 42.
Stress-Slip Diagrams
Pull-Out Tests

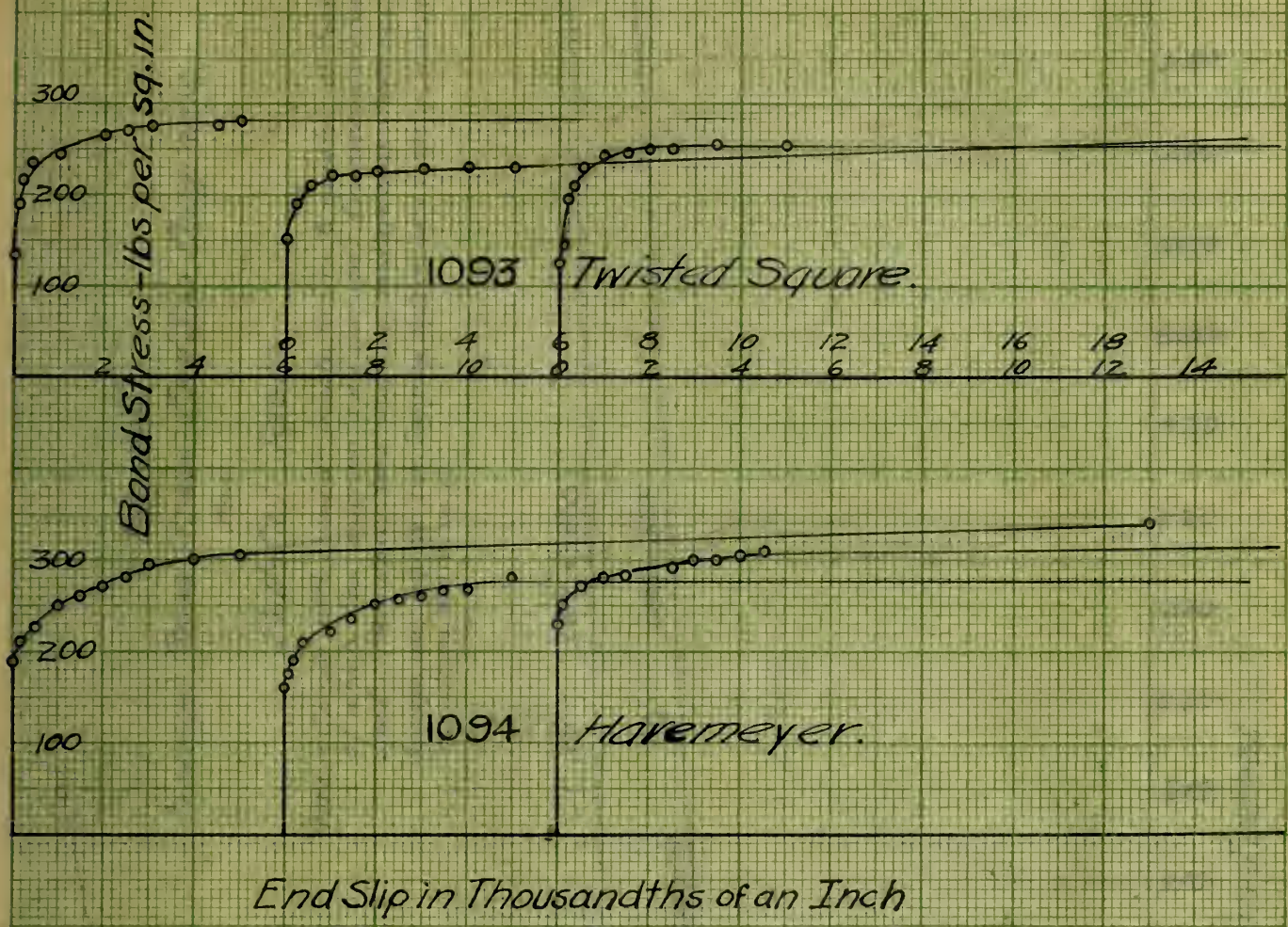

Fig. 43.
Stress-Slip Diagrams
Pull-Out Tests

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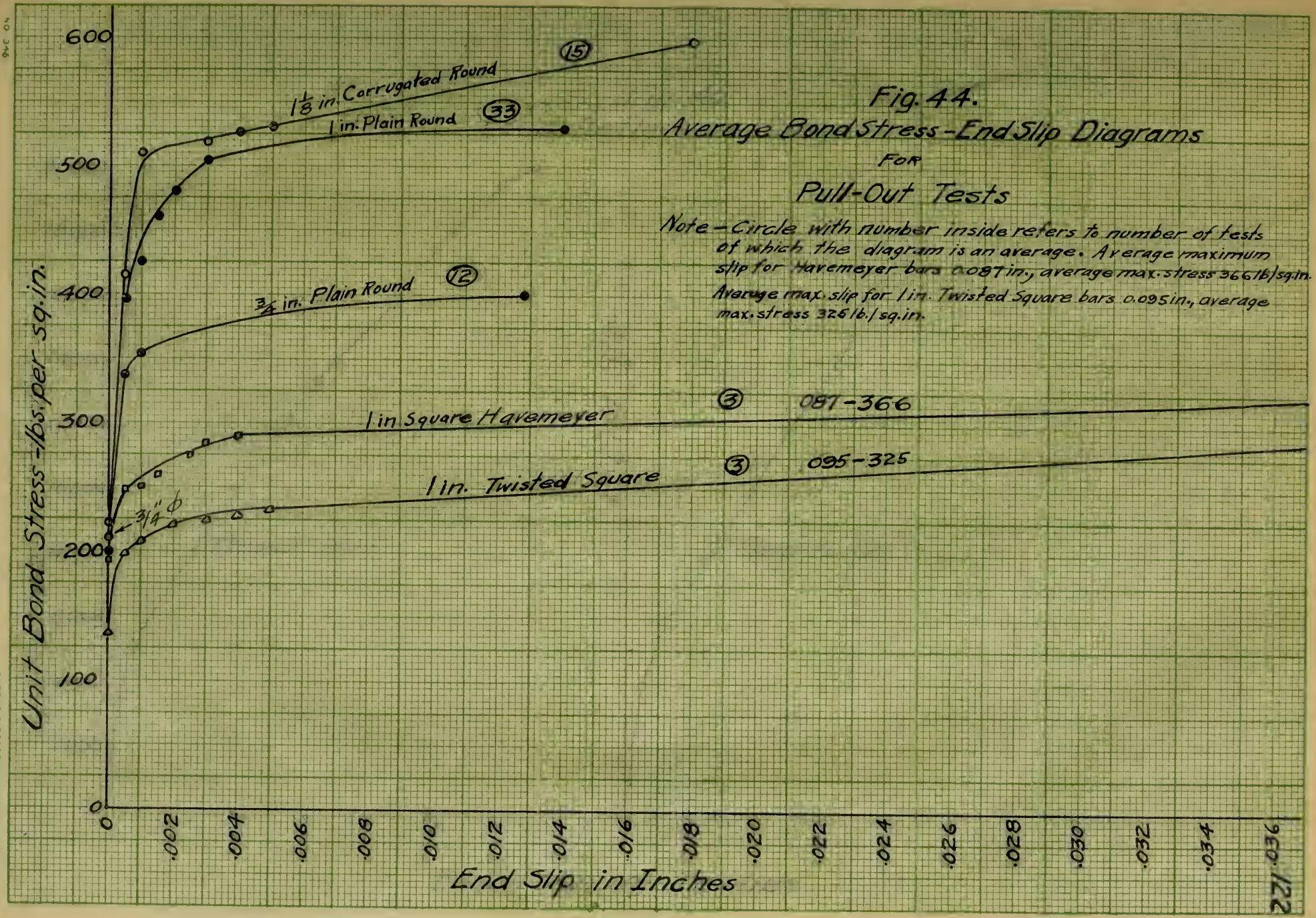

Fig. 44.
Average Bond Stress - End Slip Diagrams
FOR
Pull-Out Tests

Note — Circle with number inside refers to number of tests of which the diagram is an average. Average maximum slip for Havemeyer bars 0.087 in., average max. stress 366 lb/sq.in. Average max. slip for 1 in. Twisted Square bars 0.095 in., average max. stress 325 lb./sq.in.

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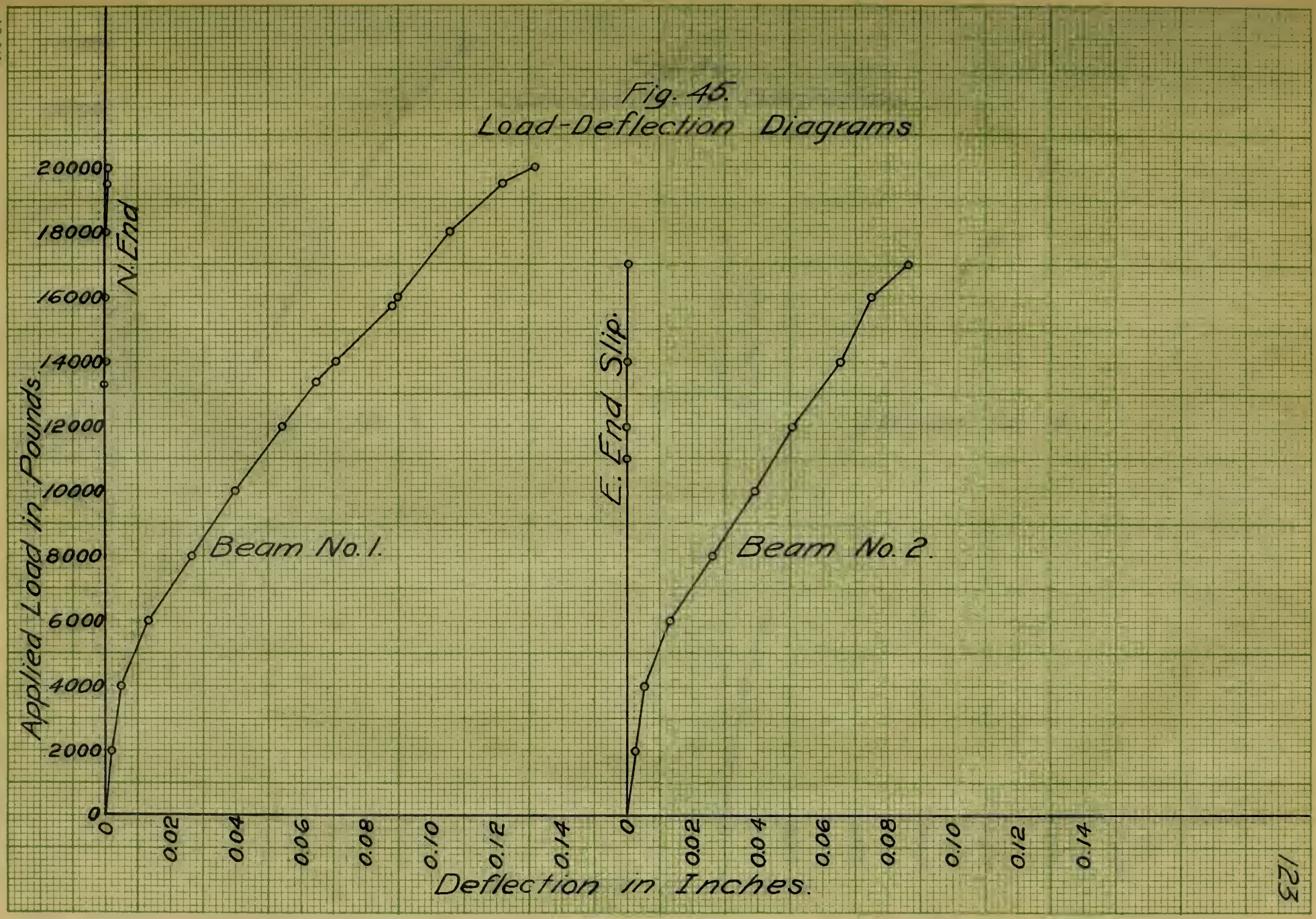

Fig. 45.
Load-Deflection Diagrams

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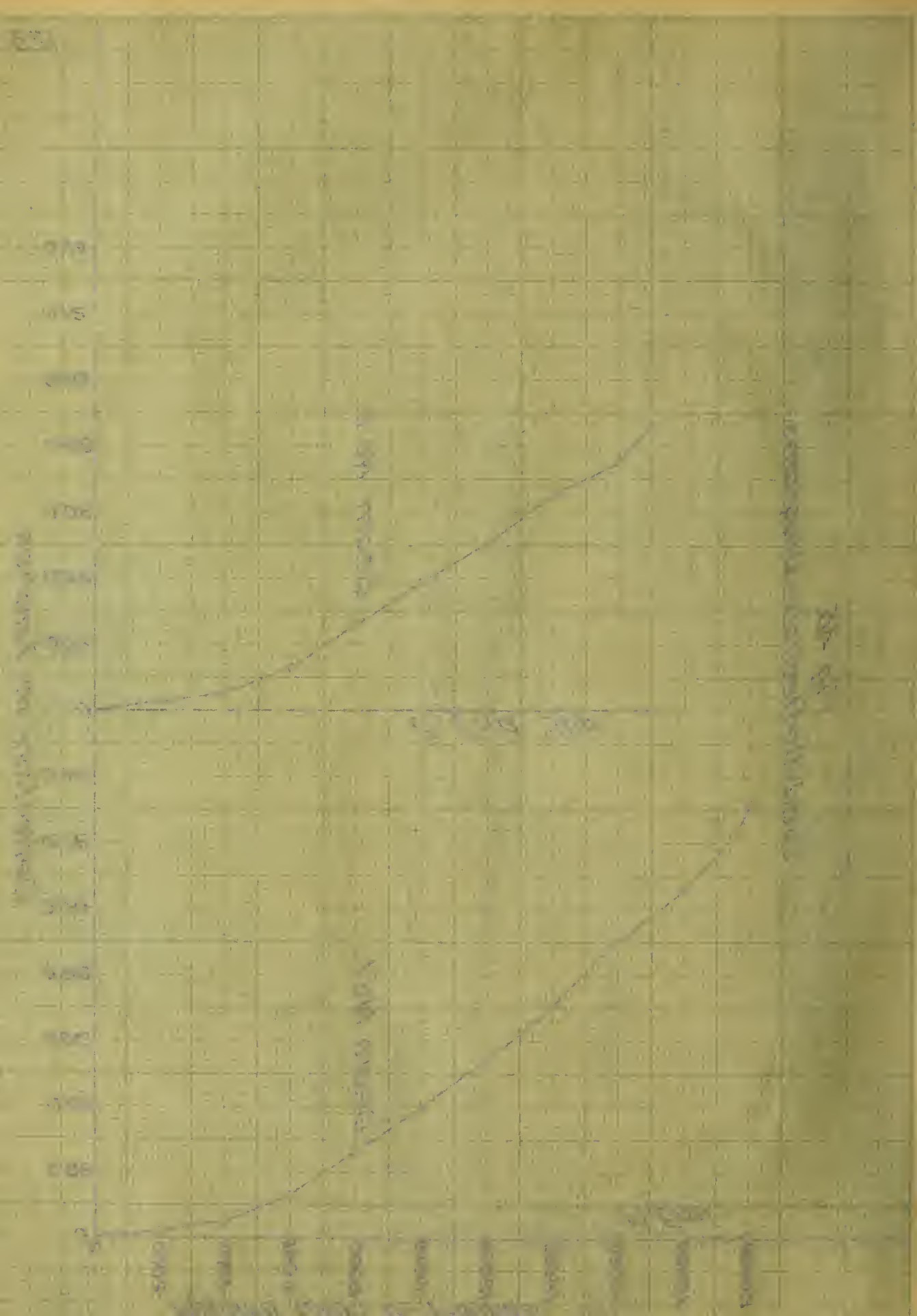


Fig. 46.
Load-Deflection Diagraram.

Deflection in inches
Load in lbs
Beam No. 2
Beam No. 3
Fig. 18

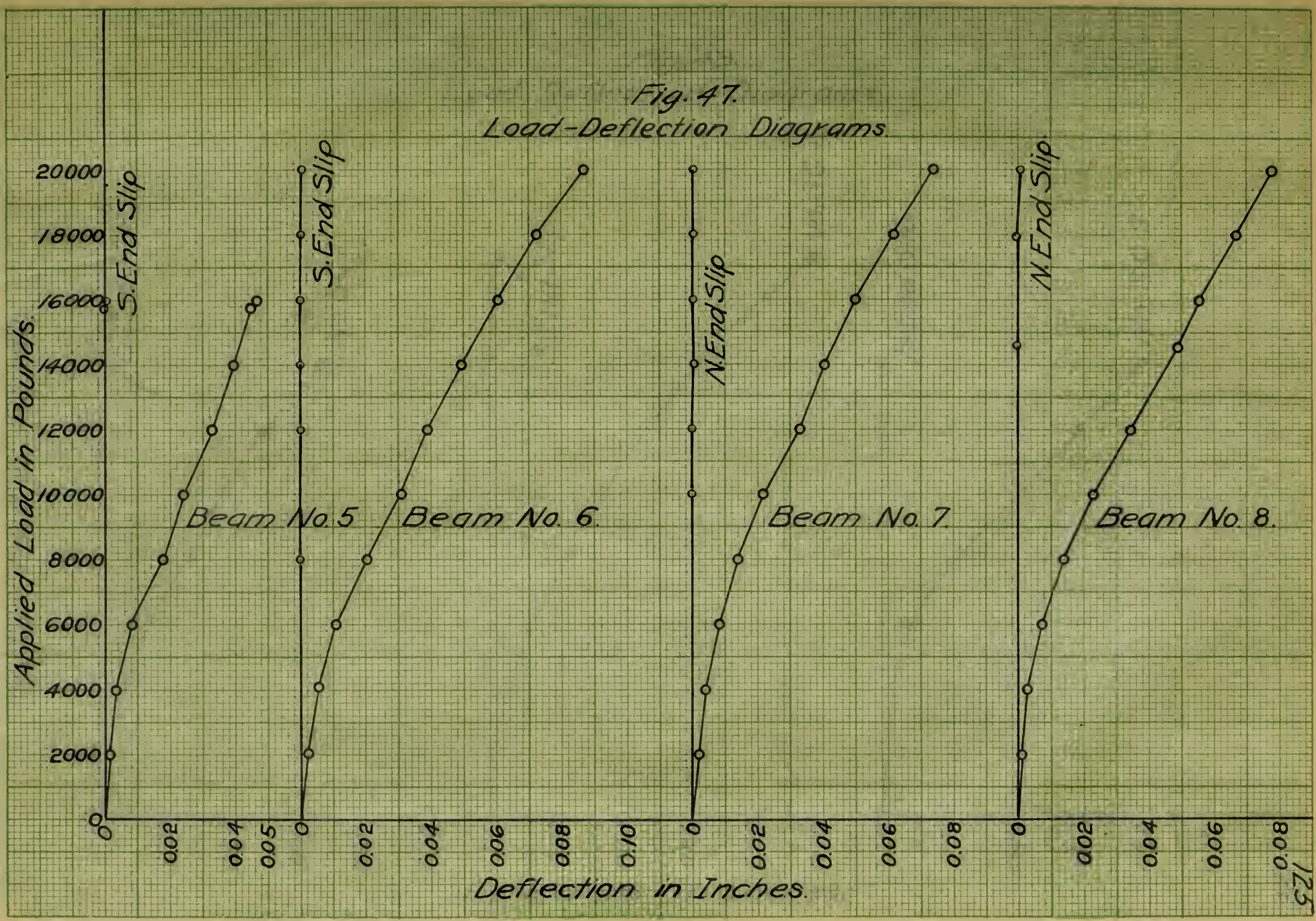
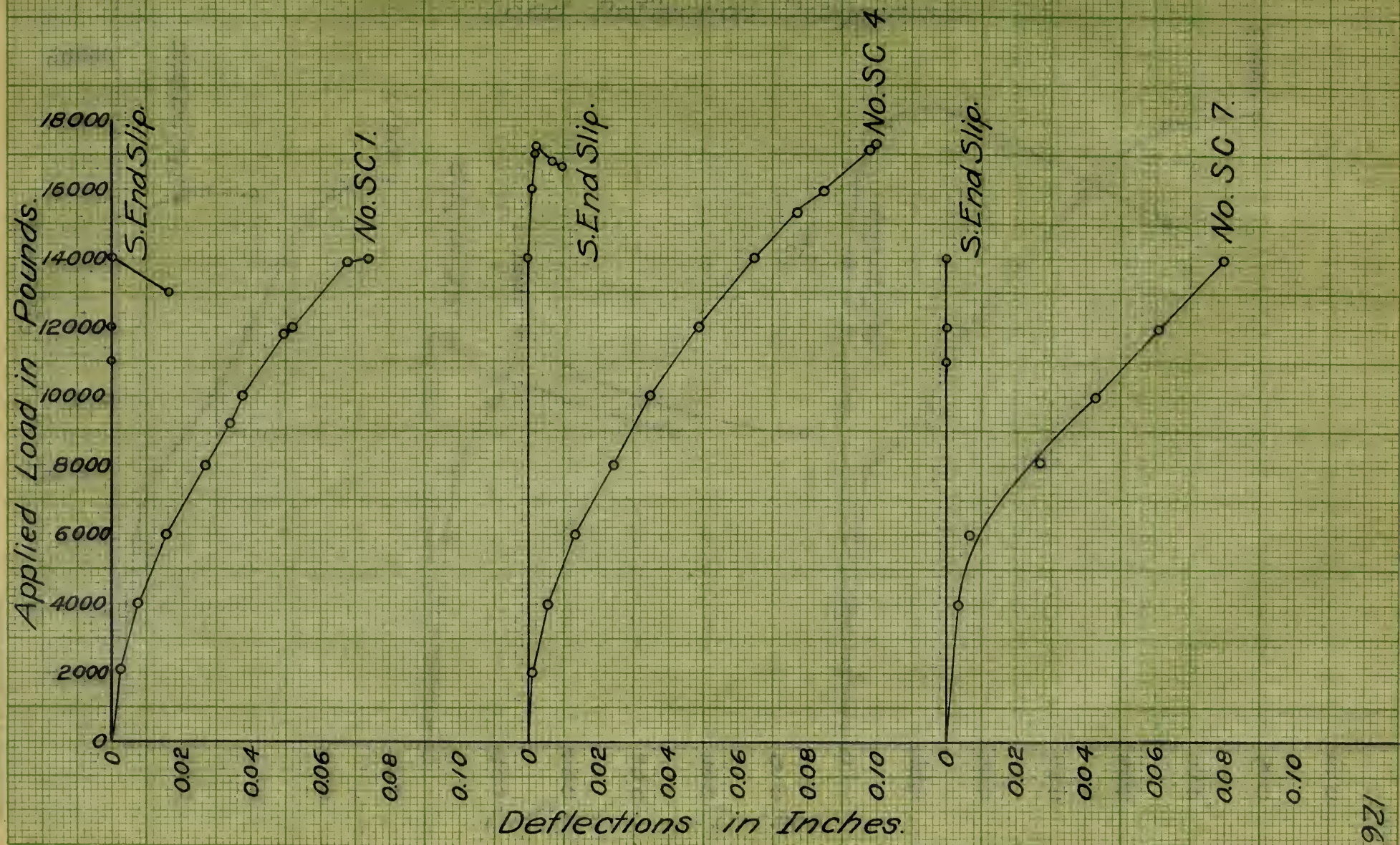


Fig. 47.
Load-Deflection Diagrams.
Applied Load in Pounds.
20000
18000
16000
14000
12000
10000
8000
6000
4000
2000
0
S. End Slip
S. End Slip
N. End Slip
N. End Slip
Beam No. 5
Beam No. 6.
Beam No. 7.
Beam No. 8.
0
0.02
0.04
0.05
0
0.02
0.04
0.06
0.08
0.10
0
0.02
0.04
0.06
0.08
0
0.02
0.04
0.06
0.08
Deflection in Inches.

Fig. 7
Comparison of Experimental Results
Air Bath 2
Air Bath 3
Air Bath 1
Air Bath 4
Experimental Results
Theoretical Results
Time in Minutes
0
500
1000
1500
2000
2500
3000
3500
4000
4500
5000
5500
6000
6500
7000
7500
8000
8500
9000
9500
10000
10500
11000
11500
12000

Fig. 48.
Load Deflection Diagrams.



Load Deflection Diagrams
Fig. 19
Deflections in Inches
No 2C1
2 Eng 21b
No 2C4
2 Eng 21b
No 2C1
2 Eng 21b
0
.005
.010
.015
.020
.025
.030
.035
.040
.045
.050
.055
.060
.065
.070
.075
.080
.085
.090
.095
.100
.105
.110
.115
.120
.125
.130
.135
.140
.145
.150
.155
.160
.165
.170
.175
.180
.185
.190
.195
.200
.205
.210
.215
.220
.225
.230
.235
.240
.245
.250
.255
.260
.265
.270
.275
.280
.285
.290
.295
.300
.305
.310
.315
.320
.325
.330
.335
.340
.345
.350
.355
.360
.365
.370
.375
.380
.385
.390
.395
.400
.405
.410
.415
.420
.425
.430
.435
.440
.445
.450
.455
.460
.465
.470
.475
.480
.485
.490
.495
.500
.505
.510
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.710
.715
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.770
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.785
.790
.795
.800
.805
.810
.815
.820
.825
.830
.835
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.845
.850
.855
.860
.865
.870
.875
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.900
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.925
.930
.935
.940
.945
.950
.955
.960
.965
.970
.975
.980
.985
.990
.995
1.000
1.005
1.010
1.015
1.020
1.025
1.030
1.035
1.040
1.045
1.050
1.055
1.060
1.065
1.070
1.075
1.080
1.085
1.090
1.095
1.100
1.105
1.110
1.115
1.120
1.125
1.130
1.135
1.140
1.145
1.150
1.155
1.160
1.165
1.170
1.175
1.180
1.185
1.190
1.195

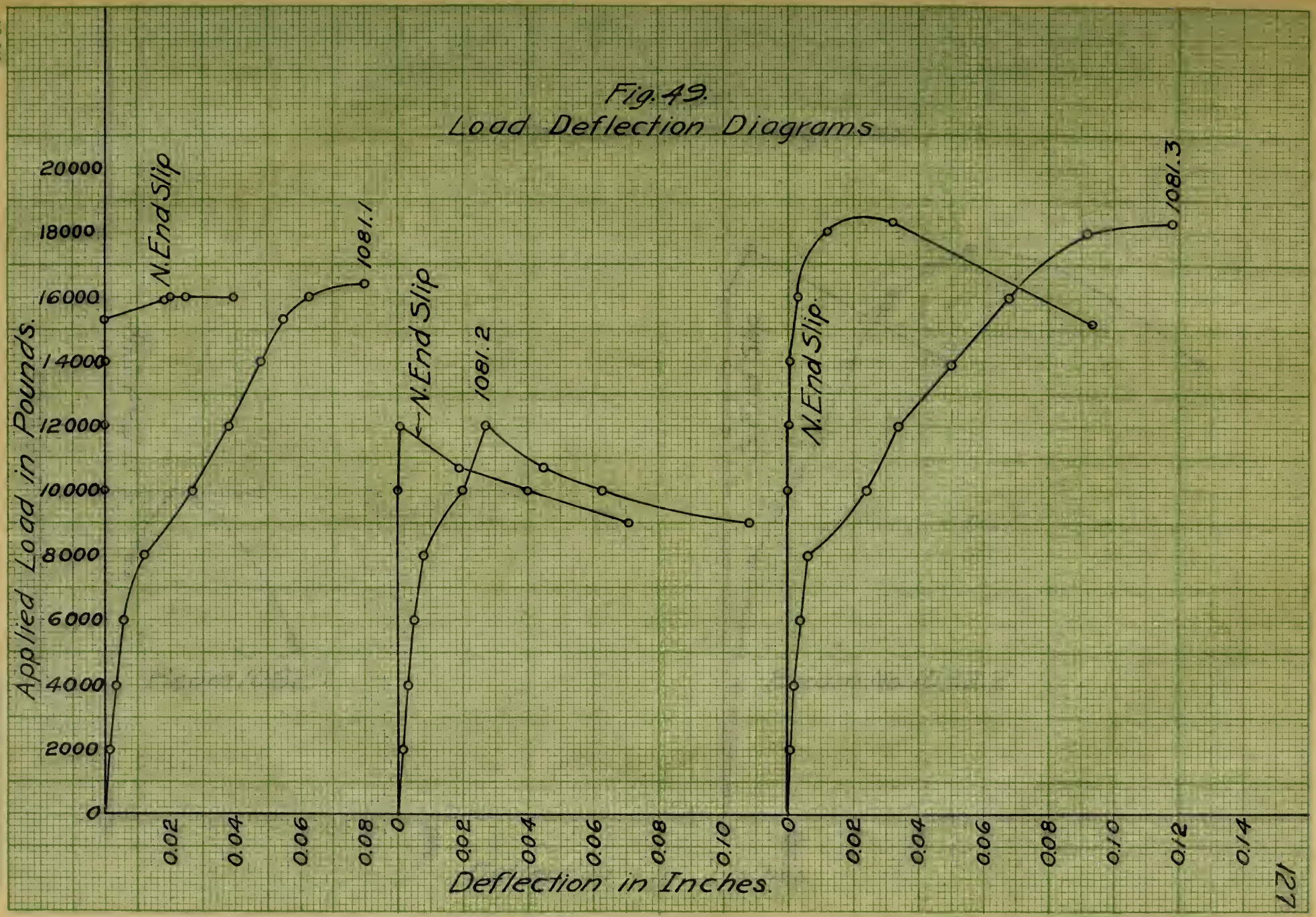
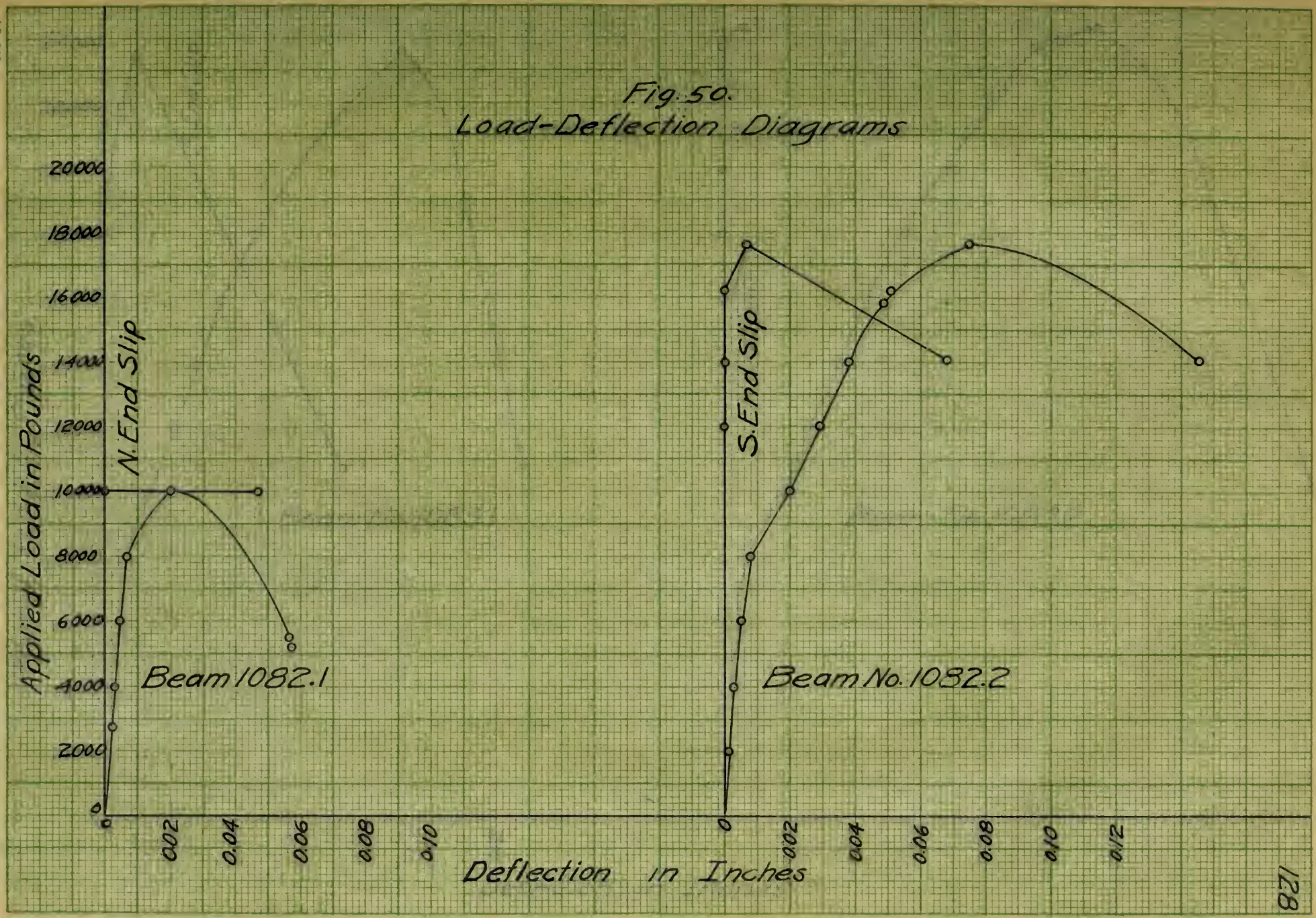


Fig. 49.
Load Deflection Diagrams
Applied Load in Pounds.
20000
18000
16000
14000
12000
10000
8000
6000
4000
2000
0
N. End Slip
1081.1
N. End Slip
1081.2
N. End Slip
1081.3
0.02
0.04
0.06
0.08
0
0.02
0.04
0.06
0.08
0.10
0
0.02
0.04
0.06
0.08
0.10
0.12
0.14
Deflection in Inches.

WEIGHT 2lb
WEIGHT 2lb
WEIGHT 2lb
WEIGHT 2lb
WEIGHT 2lb
WEIGHT 2lb
DEFLECTION IN INCHES
DEFLECTION IN INCHES
0
5000
10000
15000
20000
25000
30000
35000
40000
45000
50000



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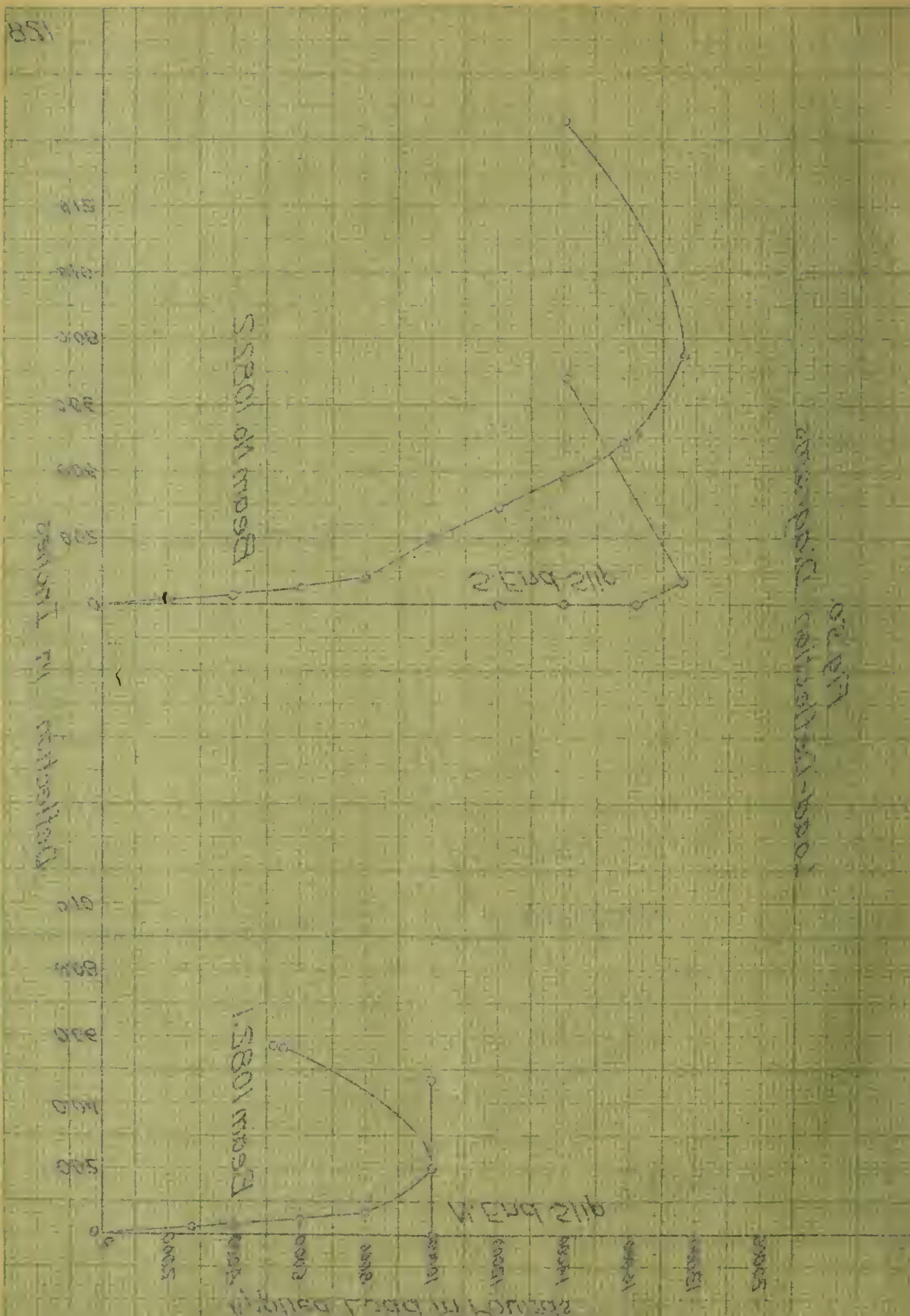

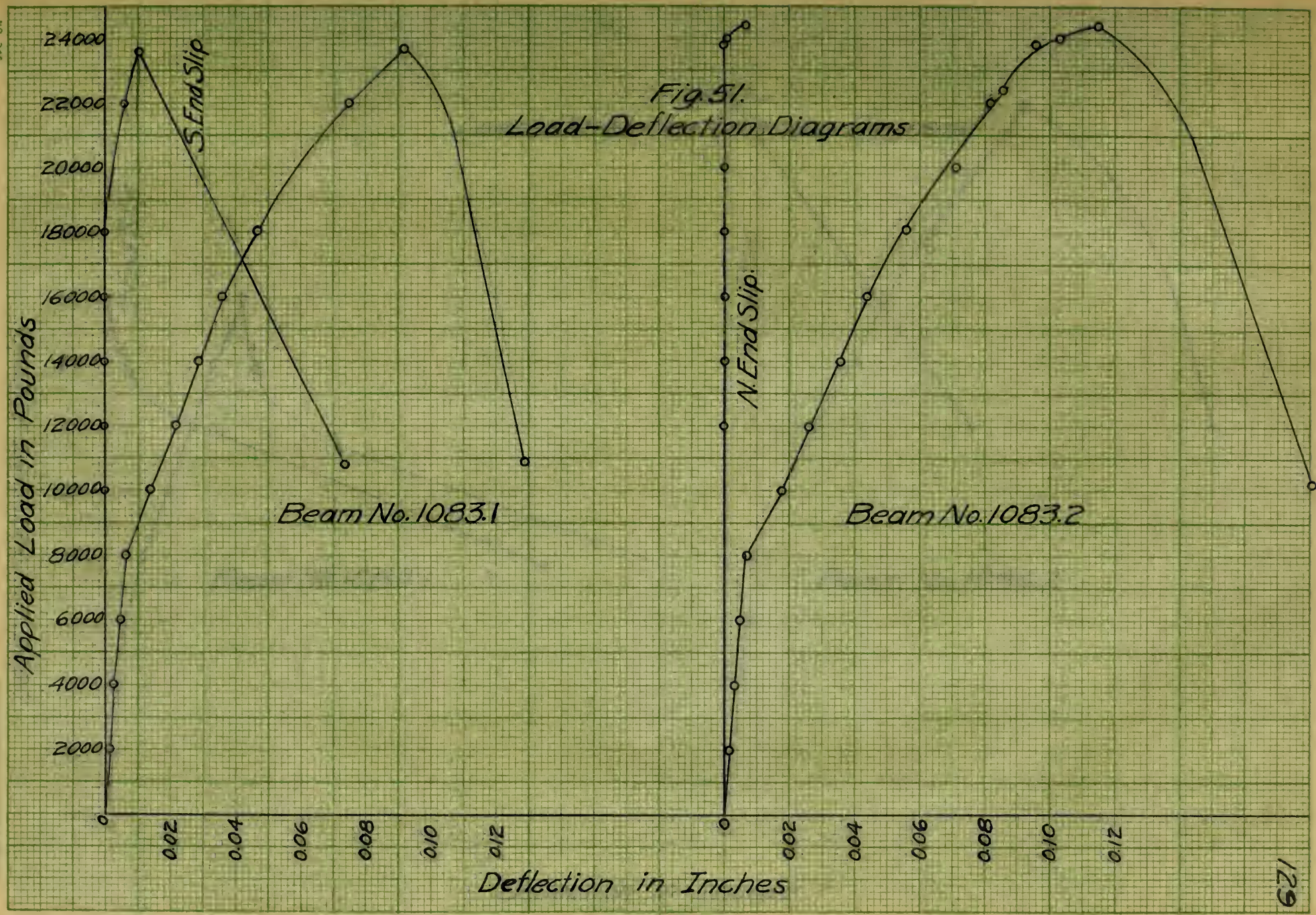

Fig. 51.
Load-Deflection Diagrams

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Deflection in Thousandths
Beam Weight
Beam Deflection
Beam Weight
Beam Deflection
Beam Weight
Beam Deflection in Inches

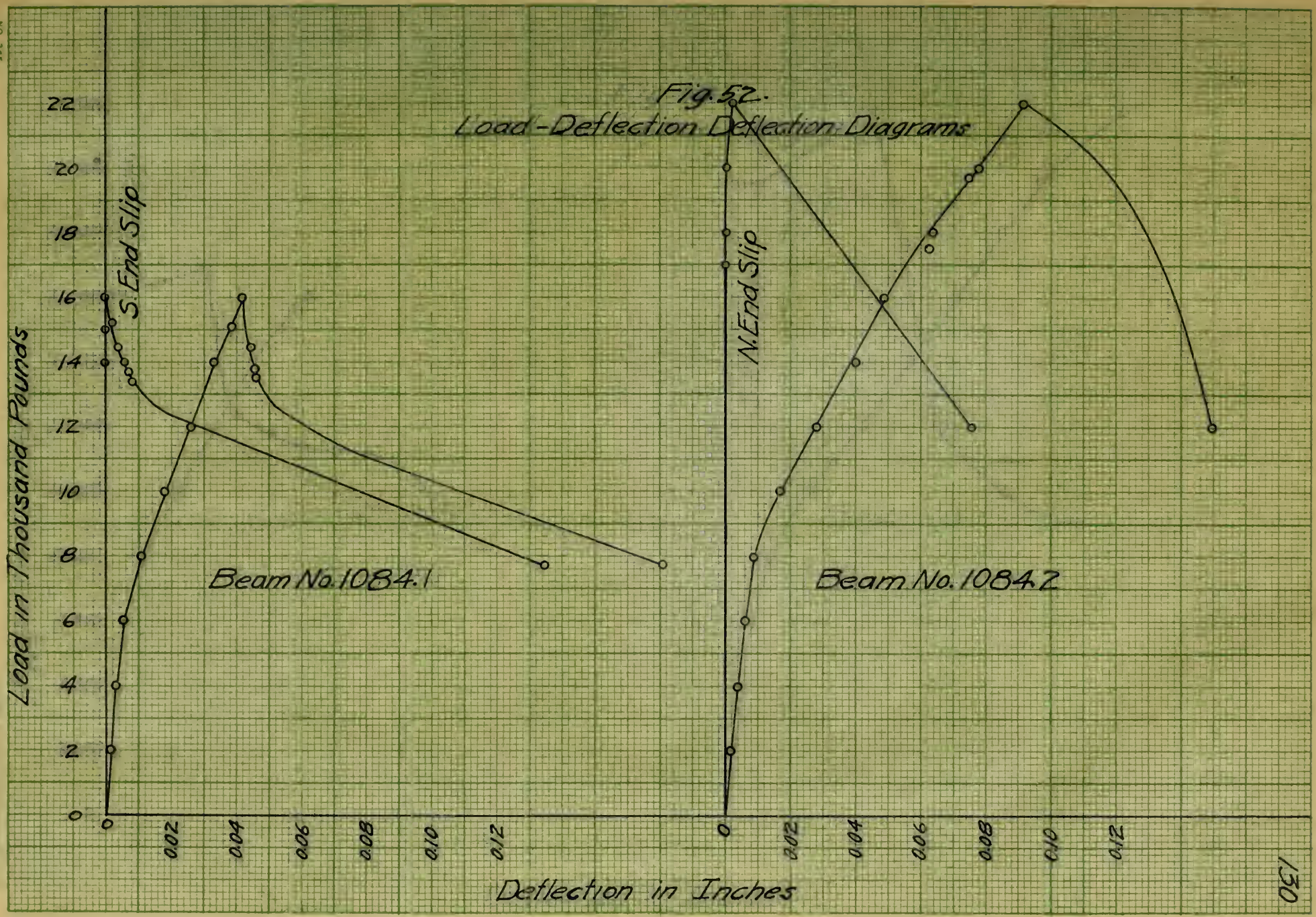

Fig. 52.
Load-Deflection Deflection Diagrams

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Deflection in Inches
Bending Moment
Bending Moment
Deflection
Air Dry
Air Dry
Deflection Curves - Test Beams

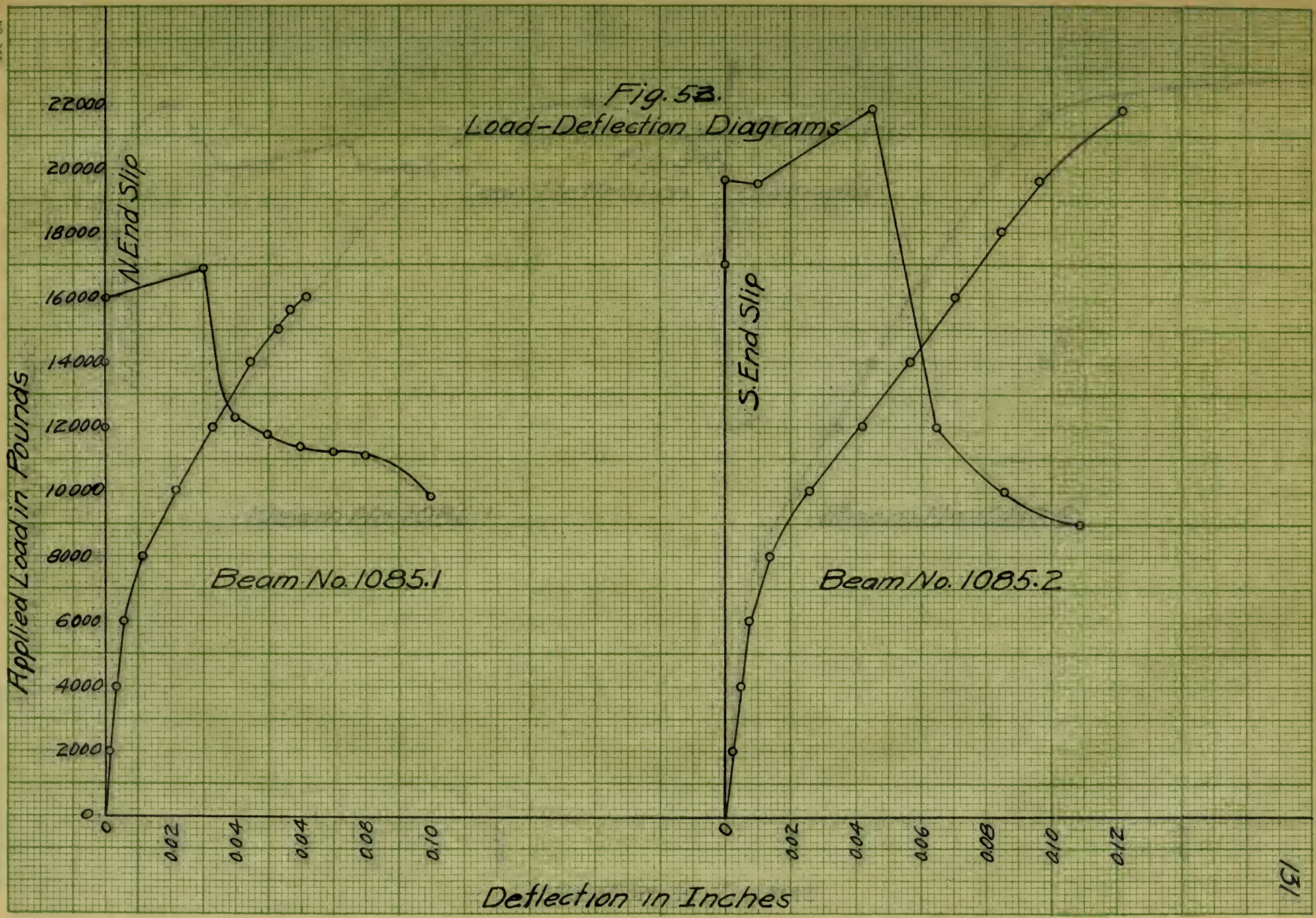

Fig. 53.
Load-Deflection Diagrams

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Fig 25 Load-Deflection Curves

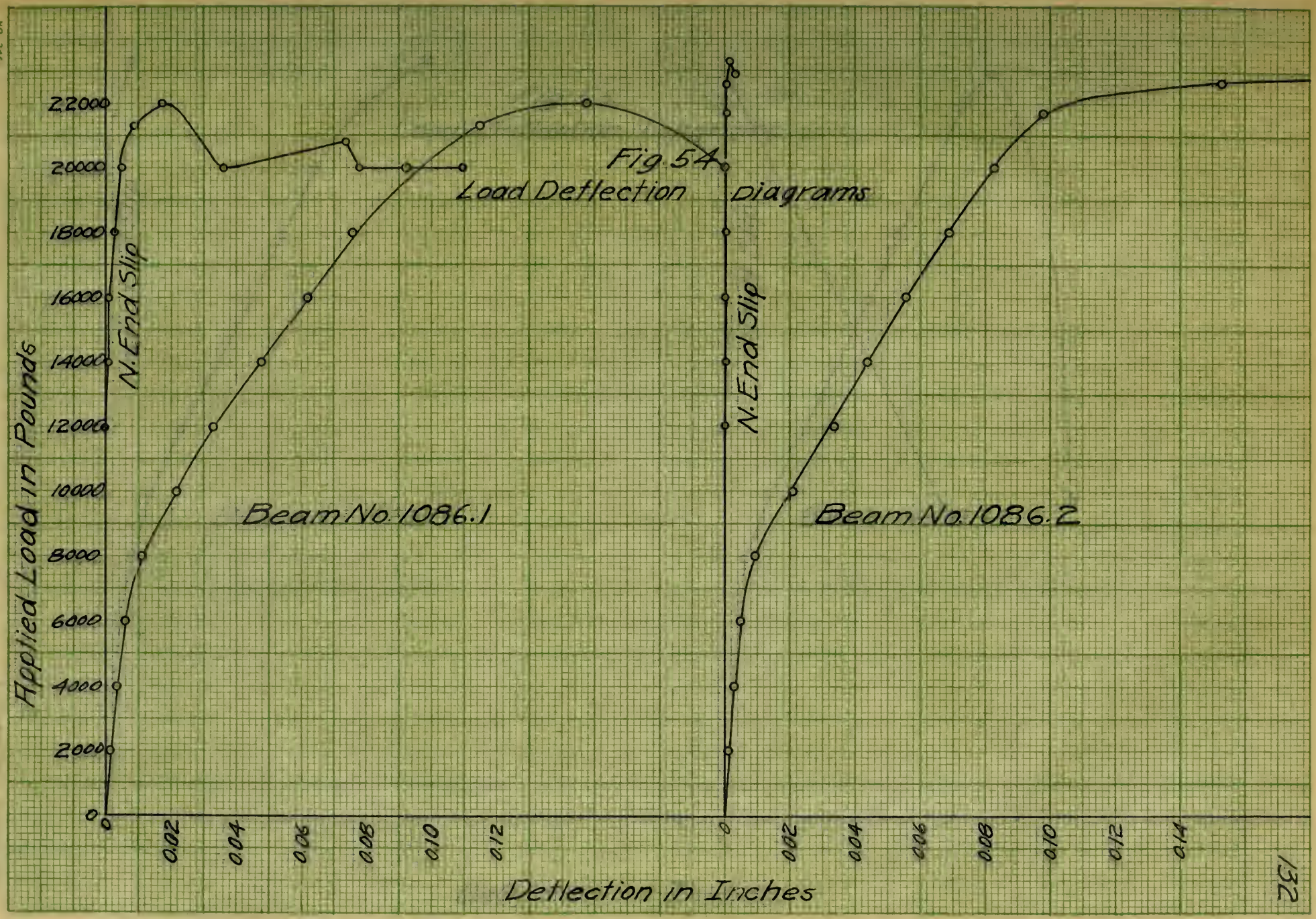

Fig. 54
Load Deflection diagrams

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Pressure
Pressure
Pressure

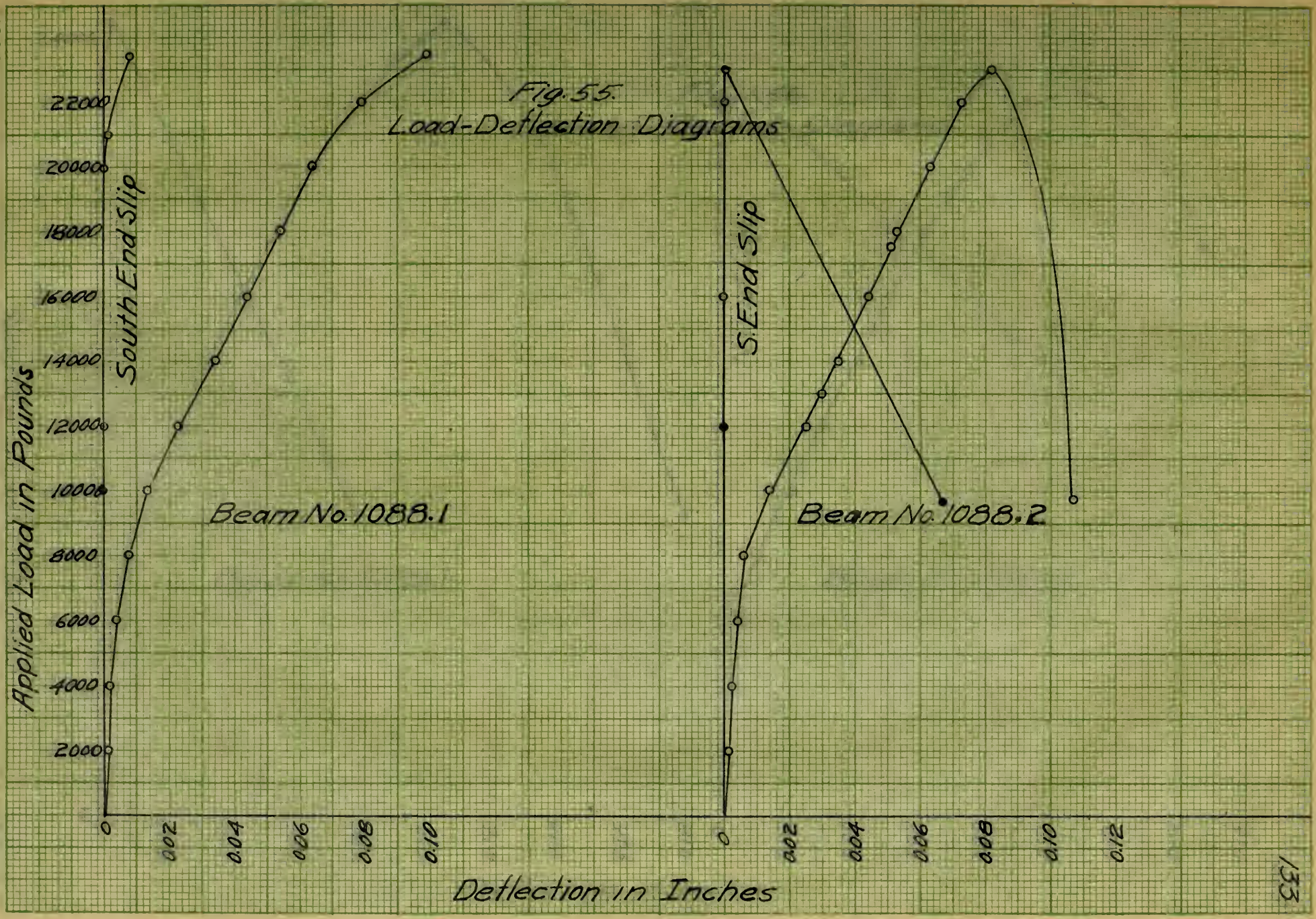


Fig. 55.
Load-Deflection Diagrams

Deflection in inches
Weight in pounds per square inch
Beam No. 1
Beam No. 2
Beam No. 3
Beam No. 4
Beam No. 5
Beam No. 6
Beam No. 7
Beam No. 8
Beam No. 9
Beam No. 10
Beam No. 11
Beam No. 12
Beam No. 13
Beam No.

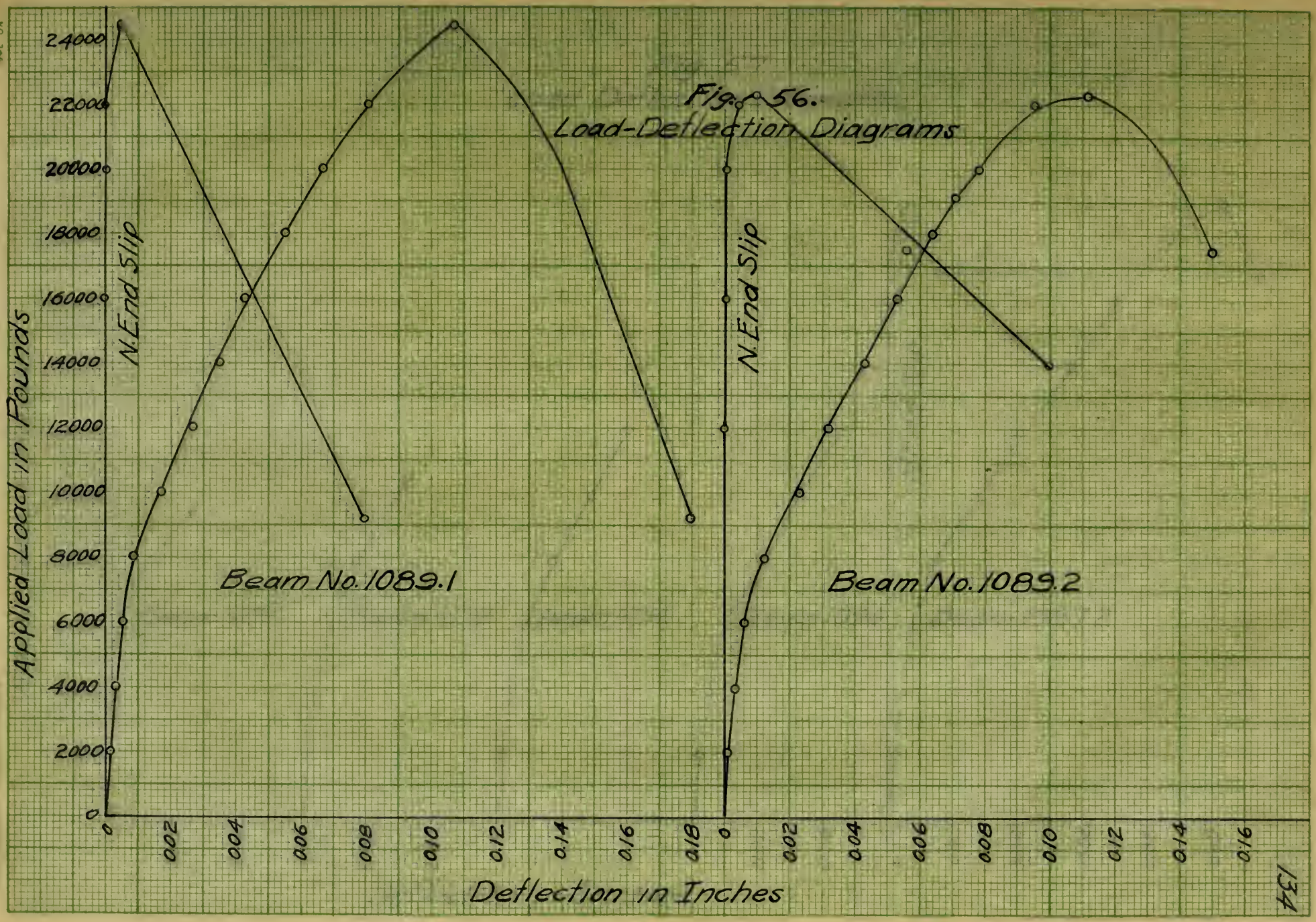


Fig. 56.
Load-Deflection Diagrams

DEFLECTION IN INCHES
BEAM WIDTH
WEIGHT
WEIGHT
BEAM WIDTH

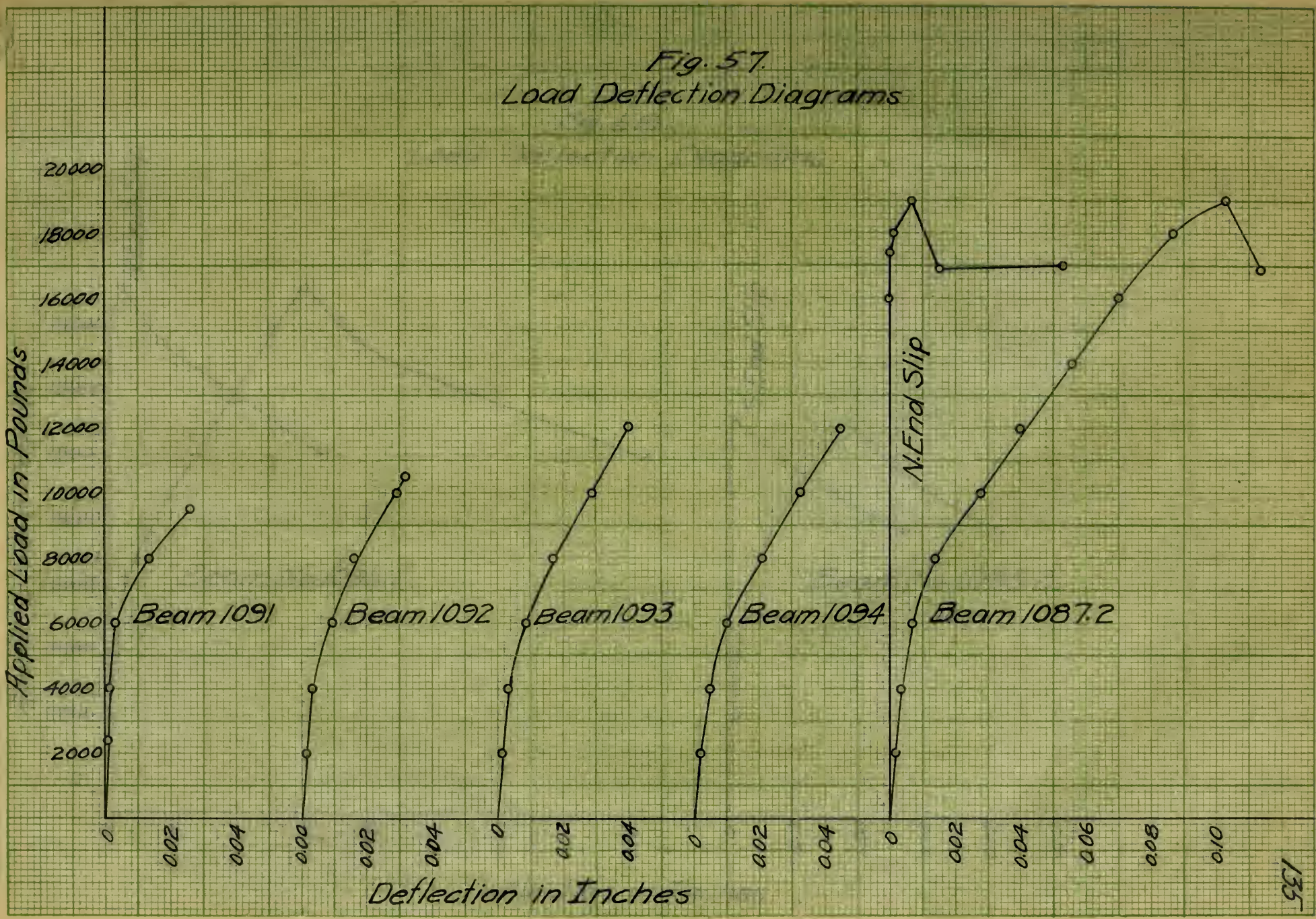
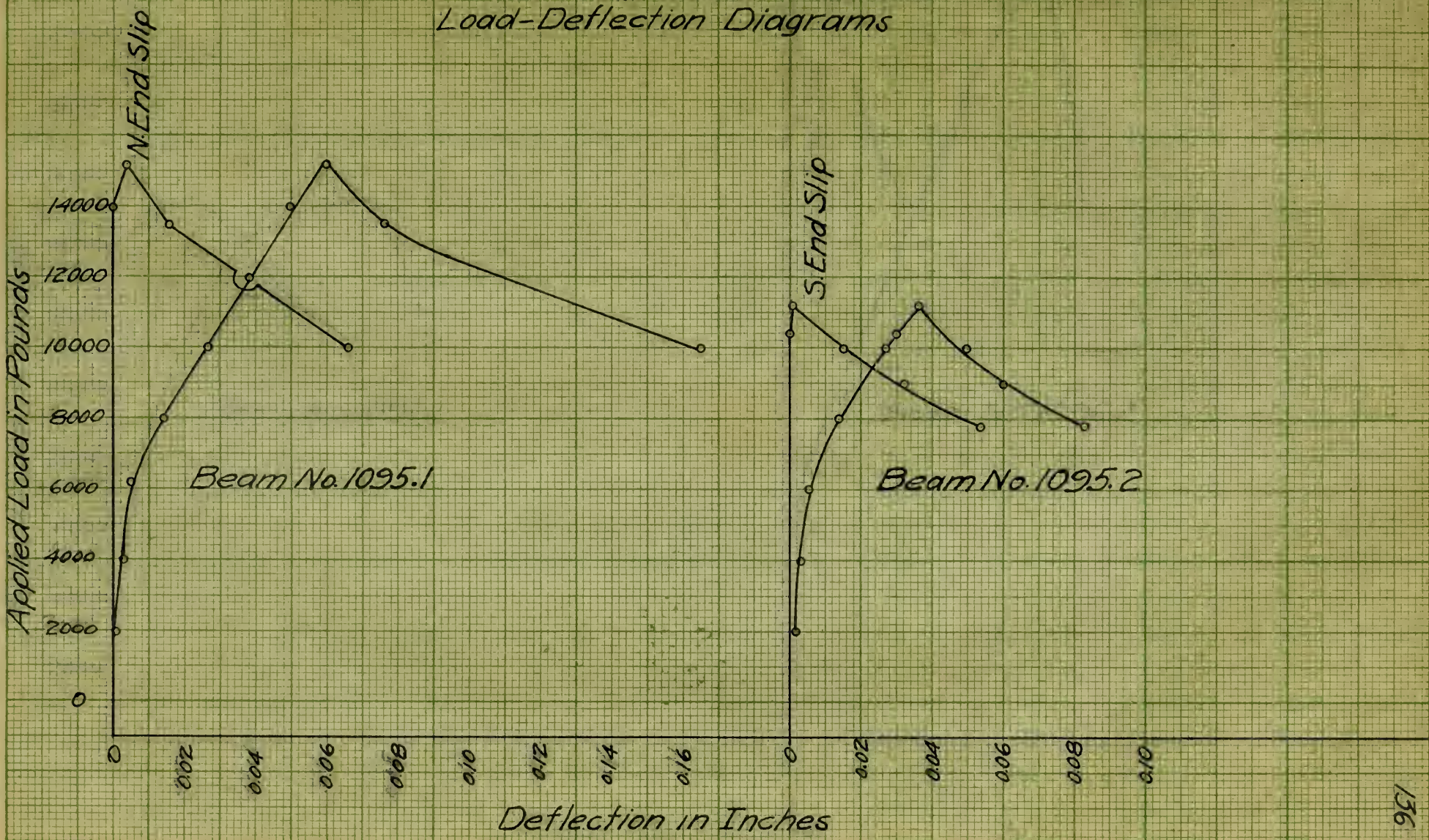


Fig. 57.
Load Deflection Diagrams
Applied Load in Pounds
20000
18000
16000
14000
12000
10000
8000
6000
4000
2000
Beam 1091
Beam 1092
Beam 1093
Beam 1094
Beam 1087.2
N. End Slip
0
0.02
0.04
0.00
0.02
0.04
0
0.02
0.04
0
0.02
0.04
0
0.02
0.04
0.06
0.08
0.10
Deflection in Inches

Fig. 21
Load Deflection Diagram

Fig. 58.
Load-Deflection Diagrams



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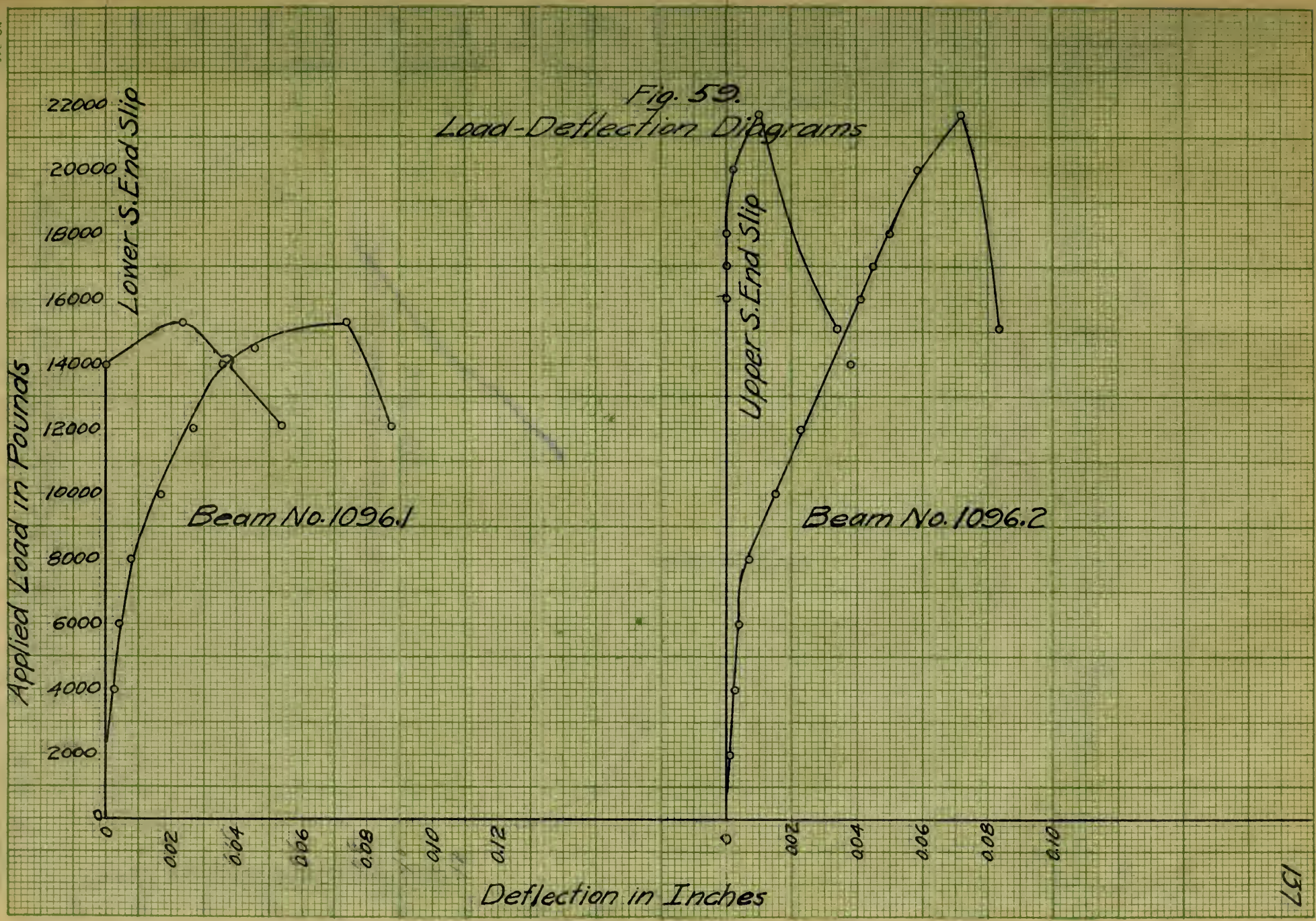
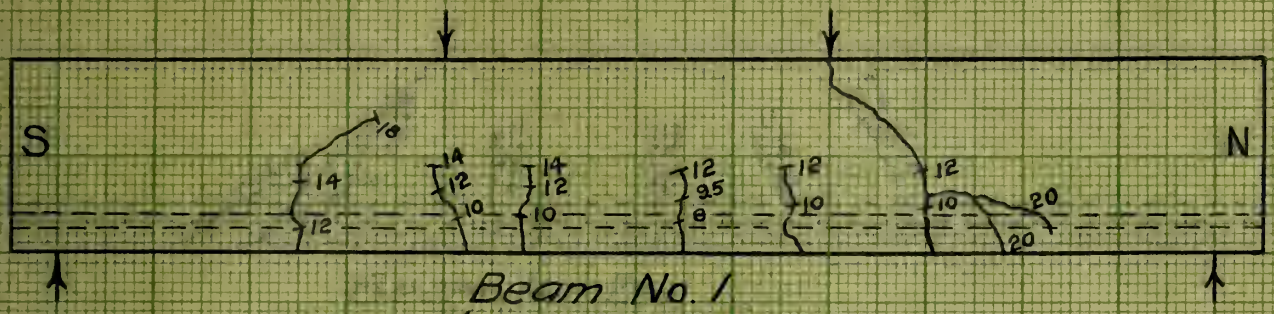


NO 346
EUGENE DIETZGEN CO CHICAGO-NEW YORK



Beam No. 1
One 1 1/16 in. Plain Round.

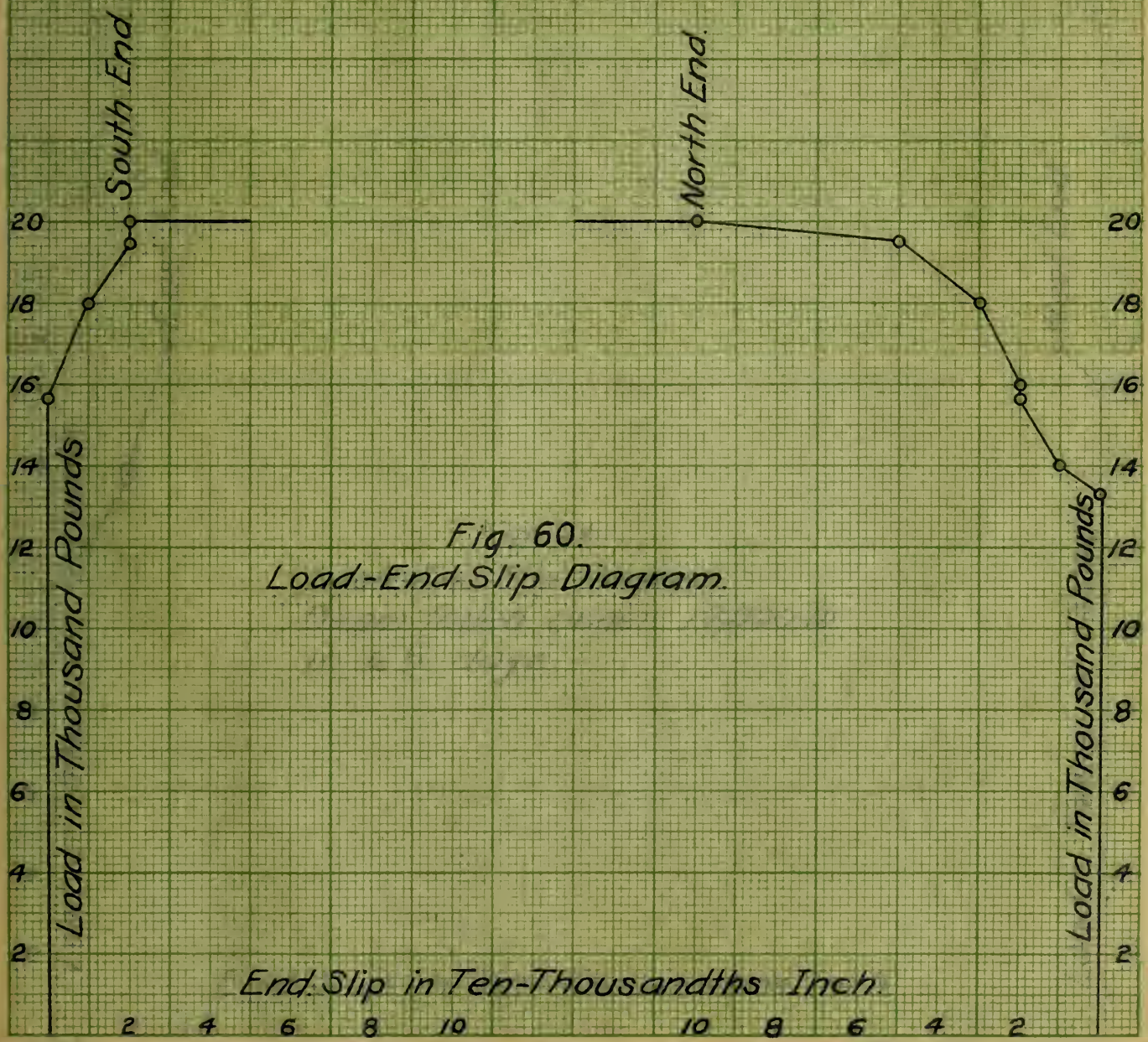


Fig. 60.
Load-End Slip Diagram.

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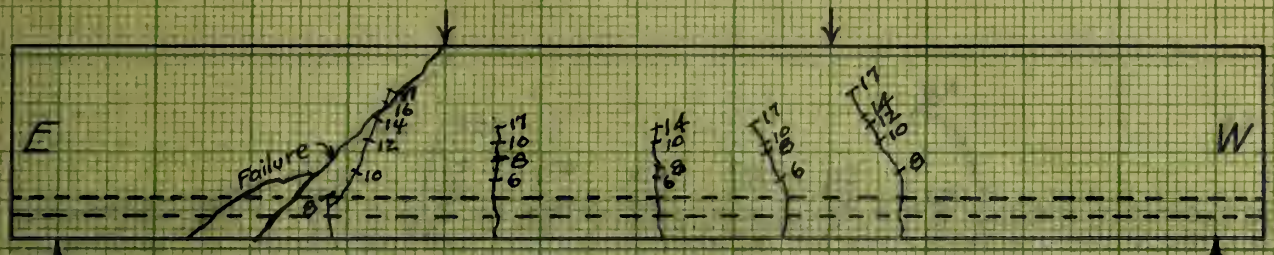
Fig 60
Load-End Slip Diagram

Beam No 1
One Main Plate Round



Beam No. 2.
One 1 1/16 in Plain Round.

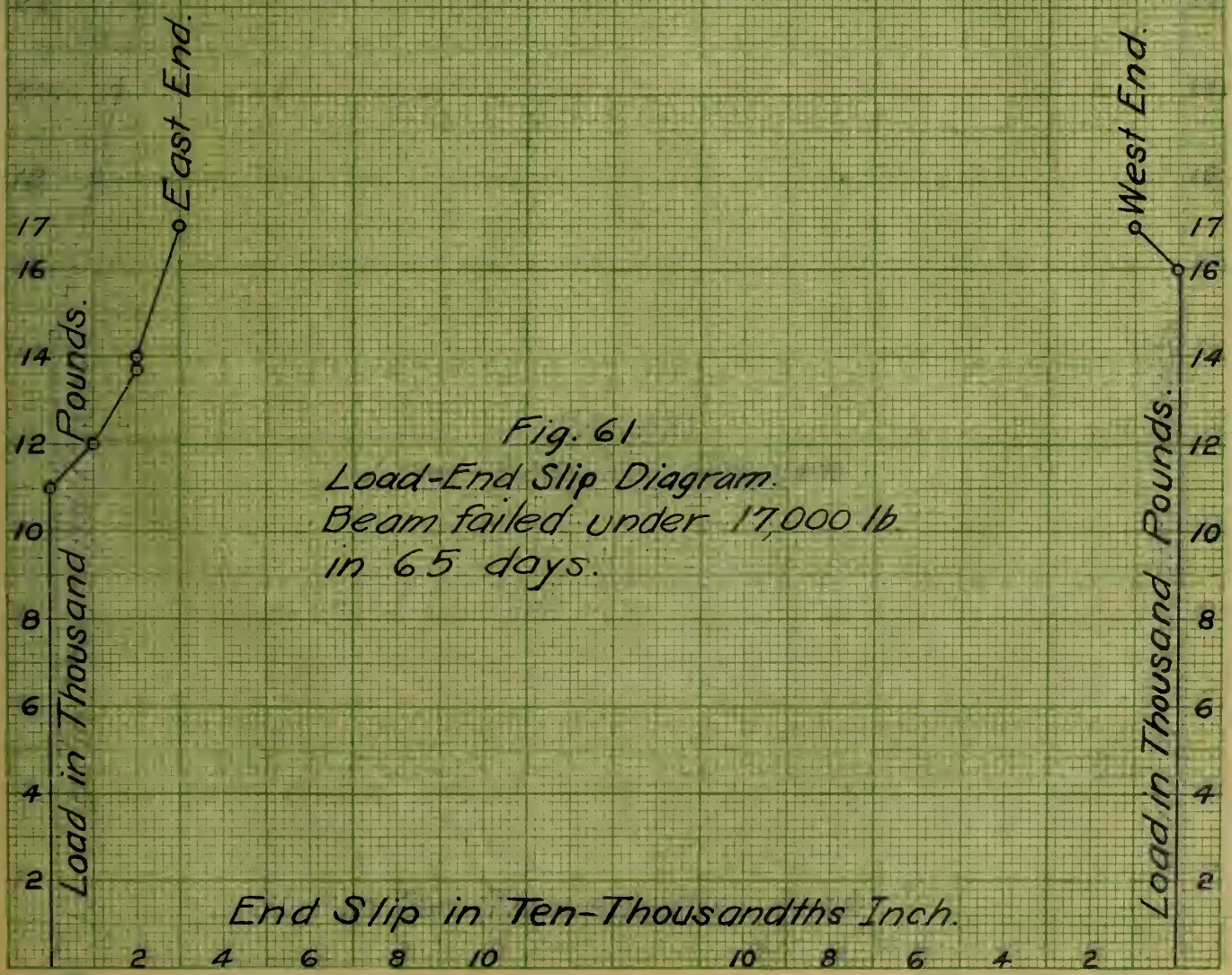


Fig. 61
Load-End Slip Diagram.
Beam failed under 17,000 lb.
in 65 days.

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EUGENE L. ETZGEN CHICAGO-NEW YORK

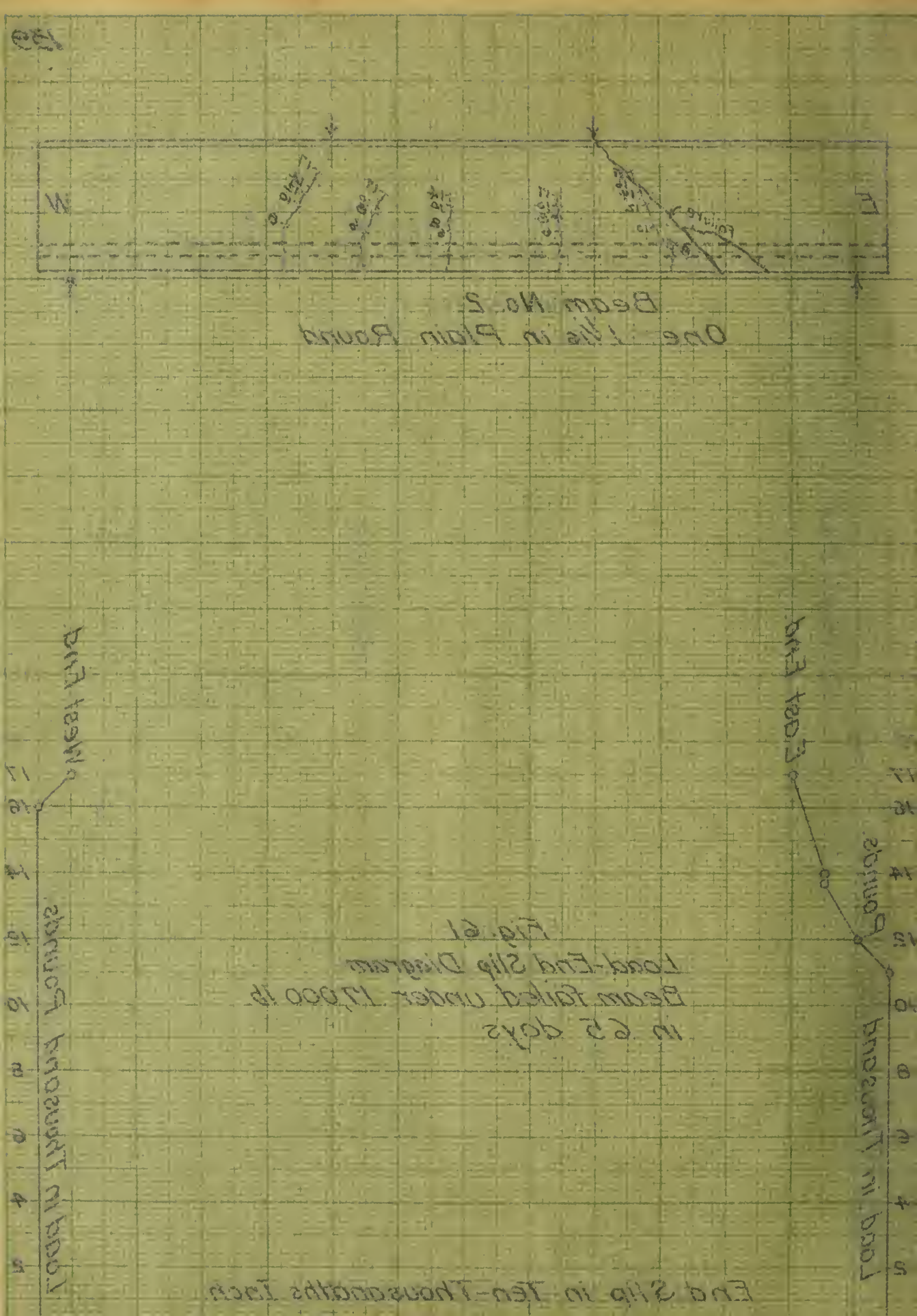
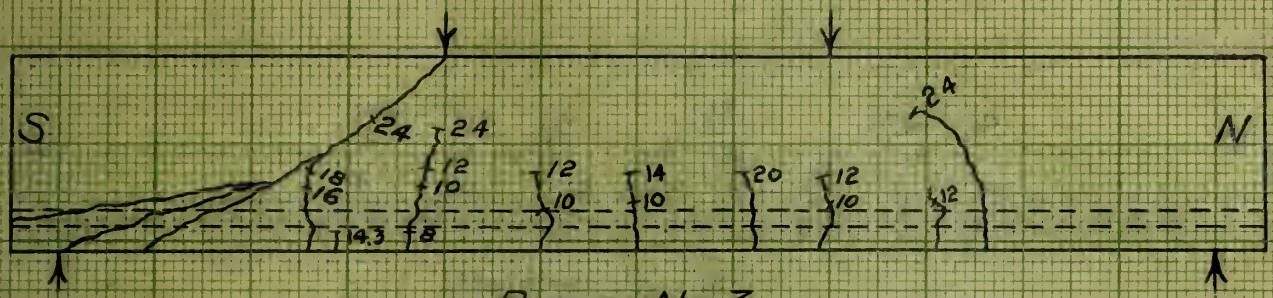


Fig. 61
Load-End Slip Diagram
Beam failed under 17,000 lb
in 65 days



Beam No. 3.
One 1 1/8 in Corrugated Round.

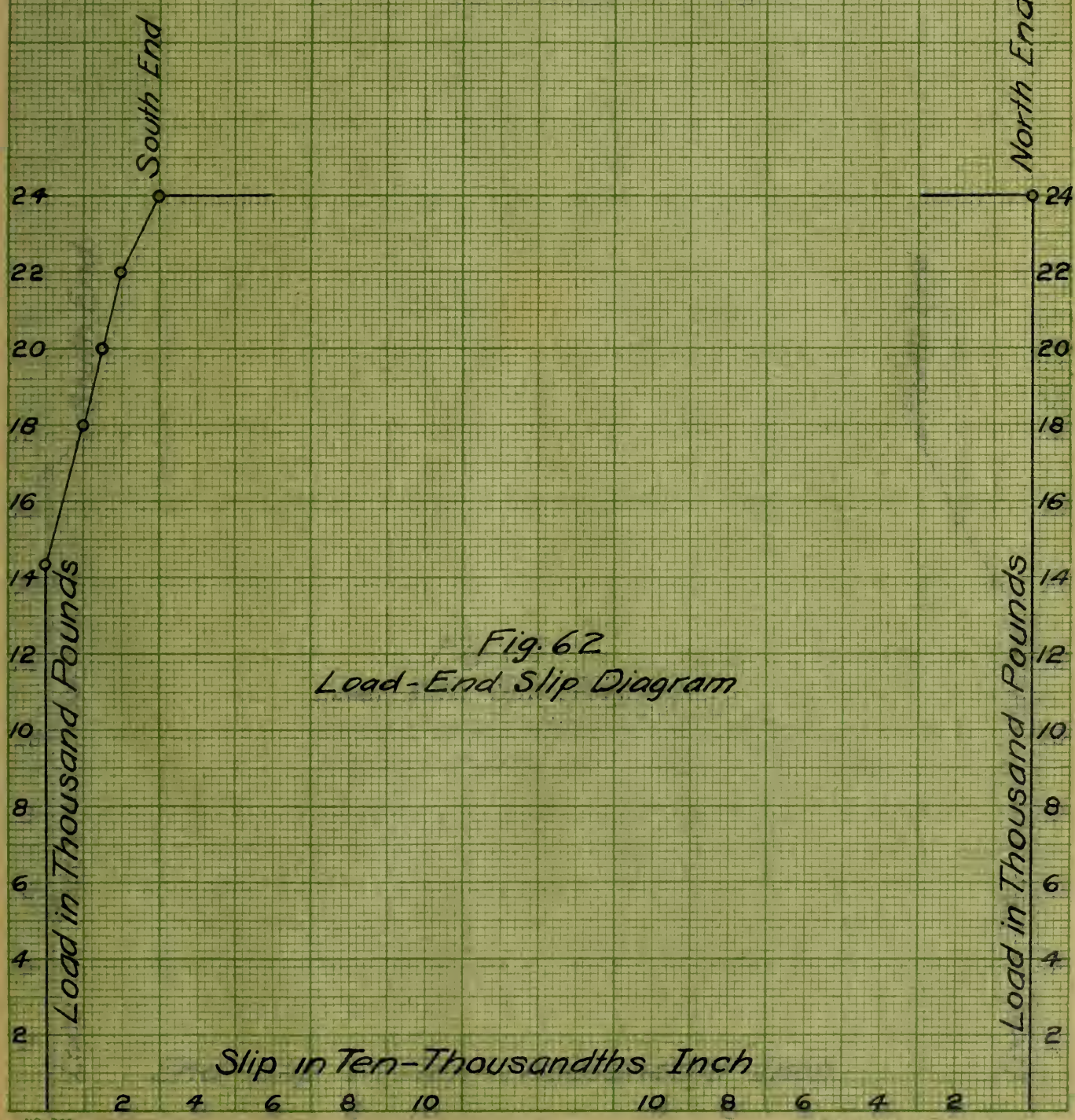


Fig. 62
Load-End Slip Diagram

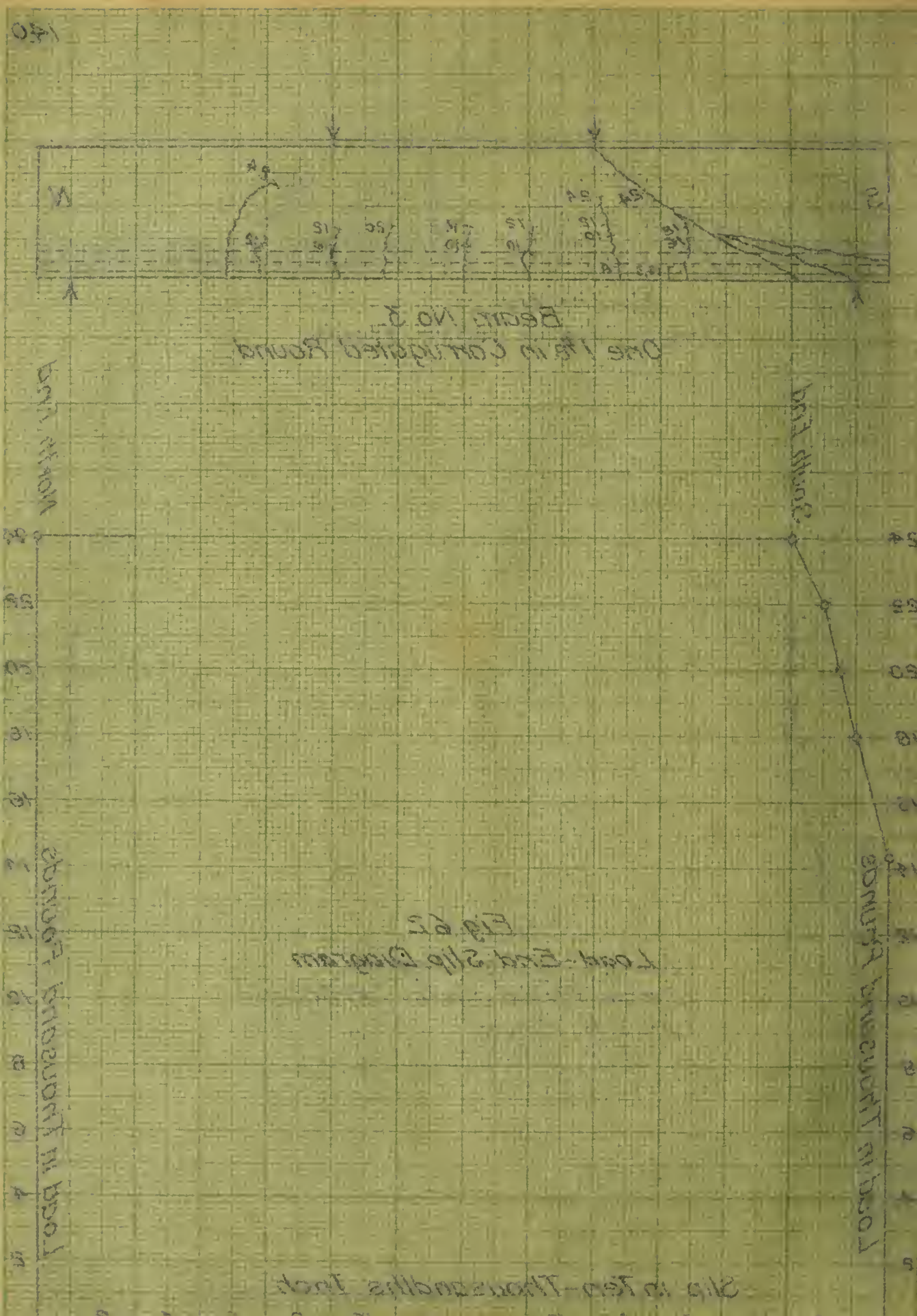
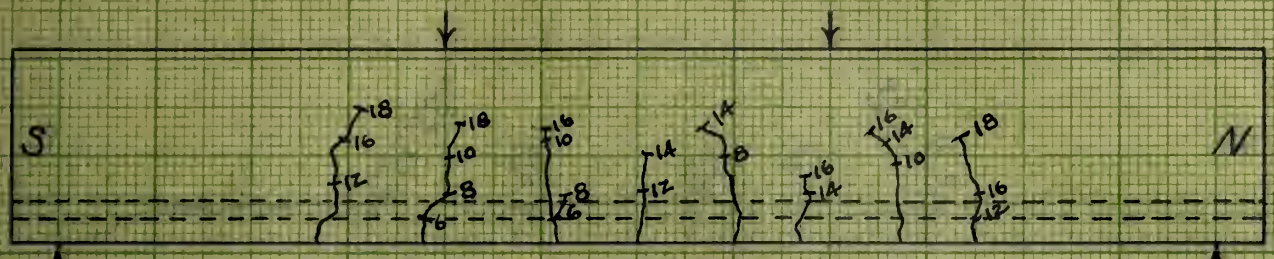


Fig 62
Load-End Slip Diagram



Beam No. 4.
One 1 1/8 in Corrugated Round

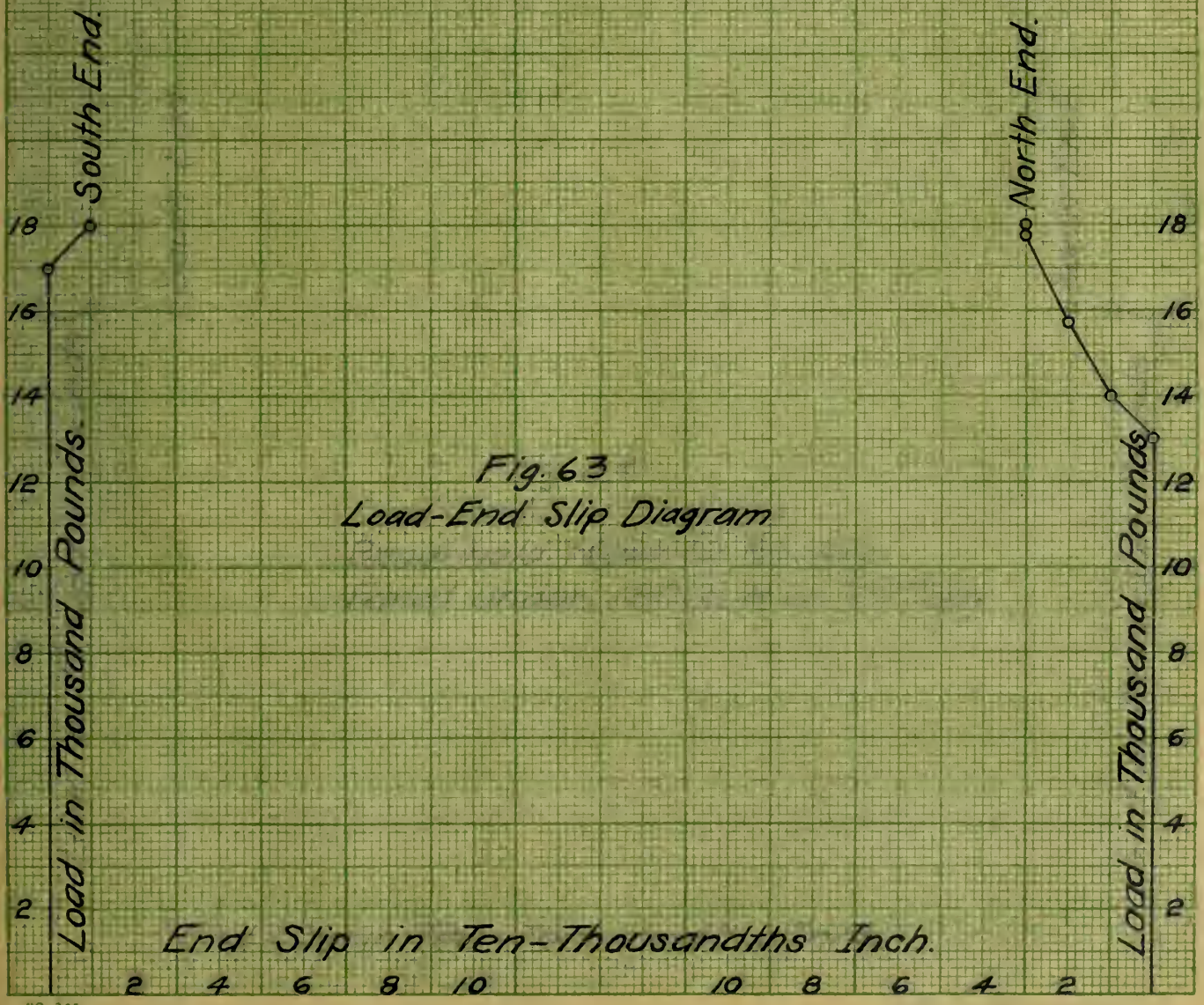


Fig. 63
Load-End Slip Diagram

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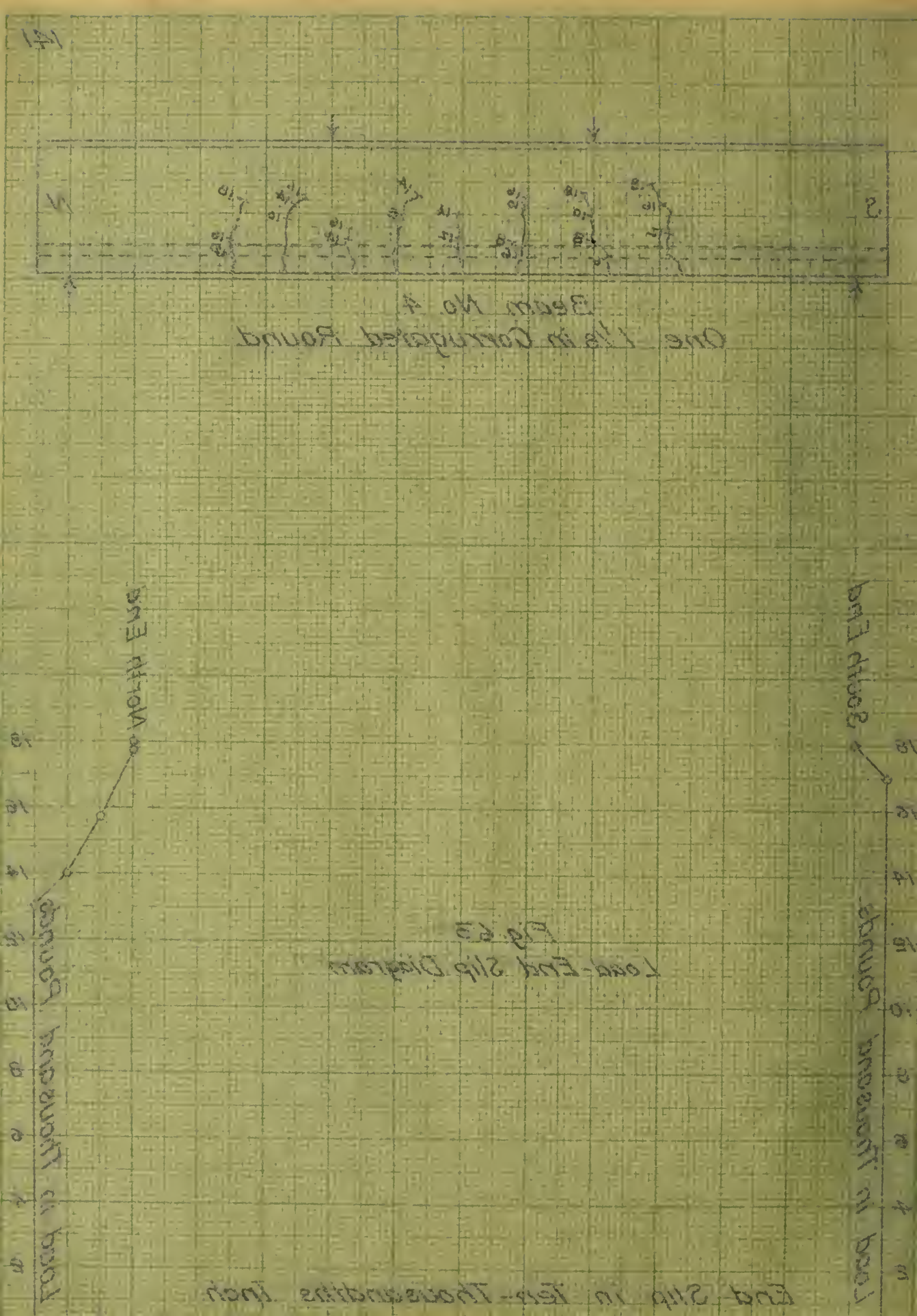
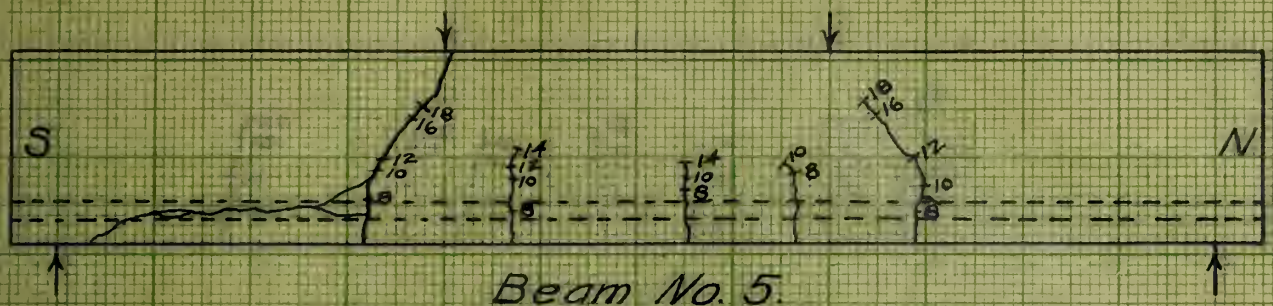


Fig. 63
Load-End Slip Diagram

Beam No. 4
One 1/8 in Corrugated Round



Beam No. 5.
One 1 in. Square Havemeyer.

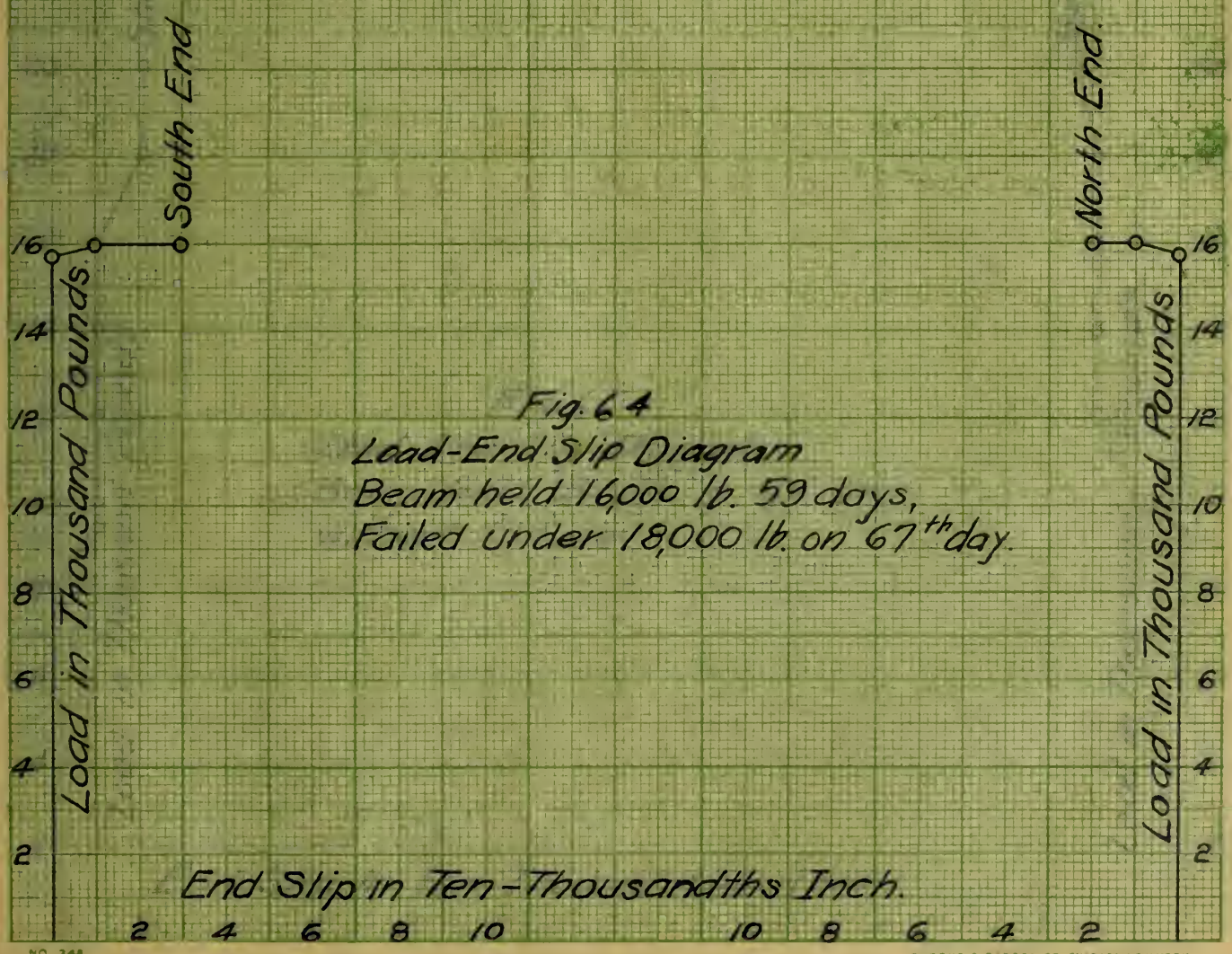


Fig. 64
Load-End Slip Diagram
Beam held 16,000 lb. 59 days,
Failed under 18,000 lb. on 67th day.

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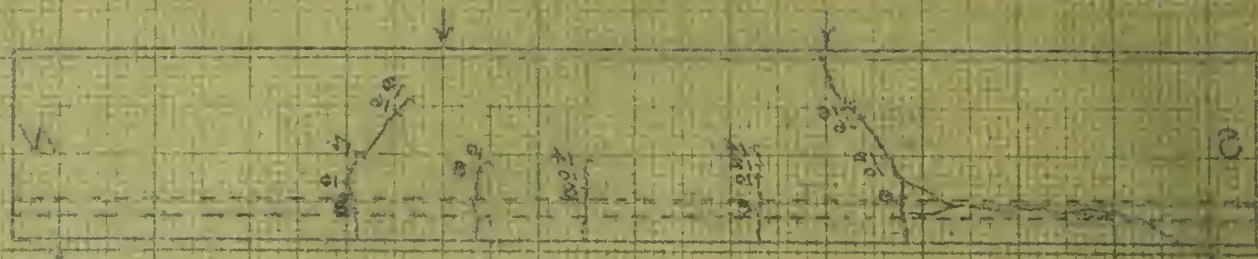


Beam No 5
One 1 in Square Haremeyer

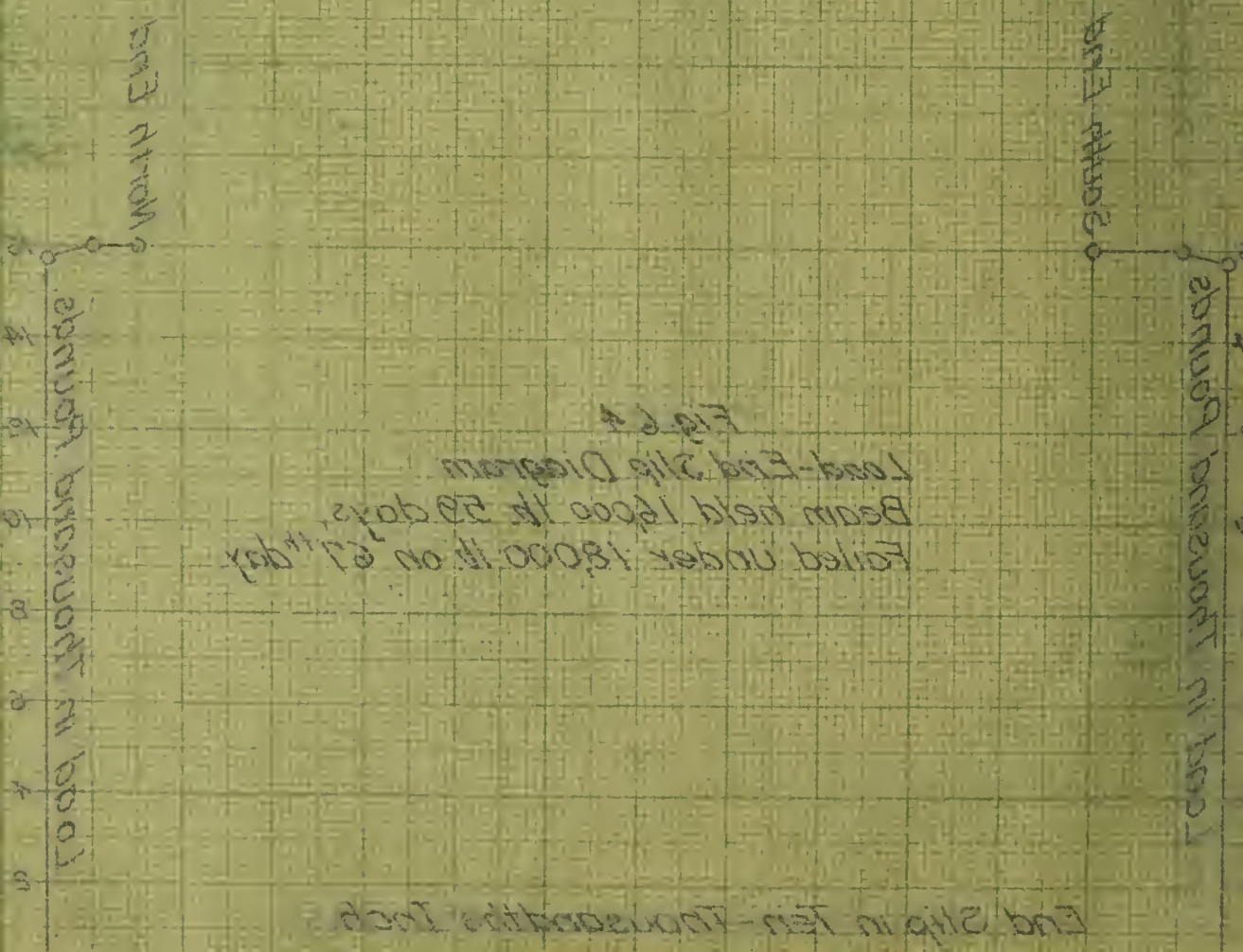
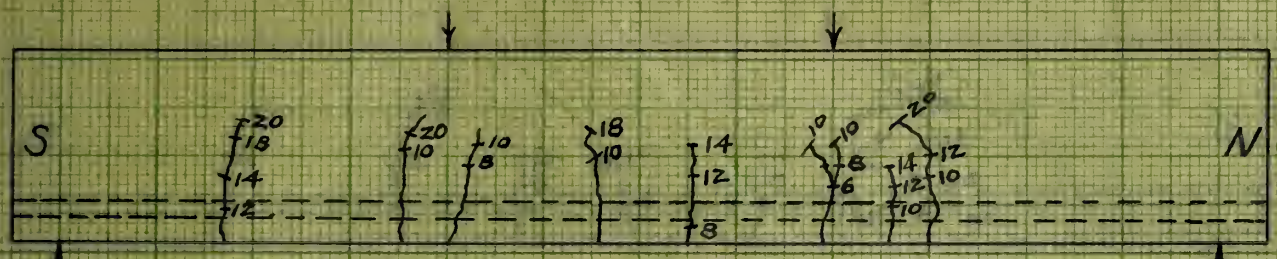


Fig 6.4
Load-End Slip Diagram
Beam held 16000 lb 59 days
Failed under 18000 lb on 67th day



Beam No. 6.
One 1 in. Square Havemeyer.

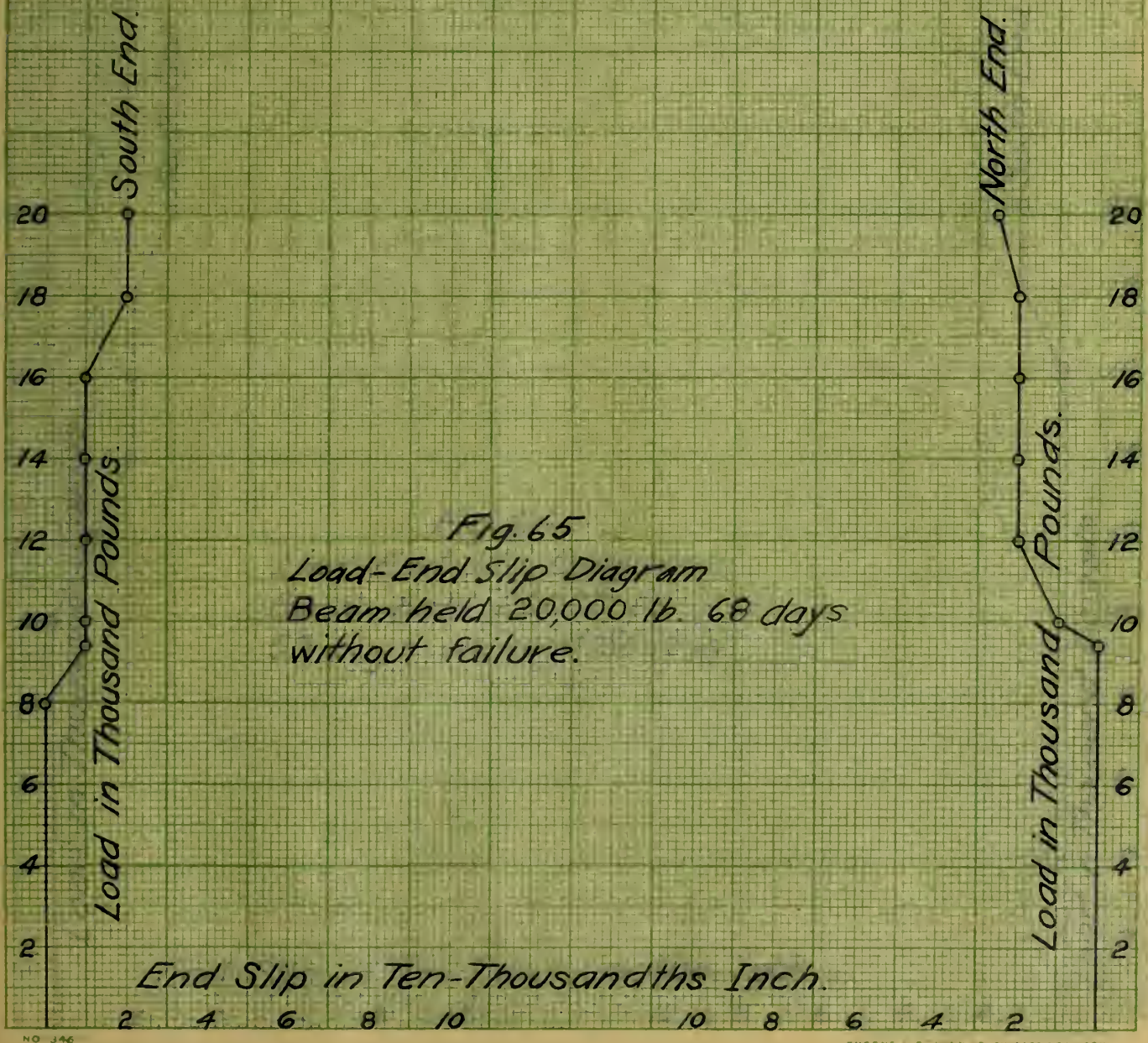


Fig. 65
Load-End Slip Diagram
Beam held 20,000 lb. 68 days
without failure.

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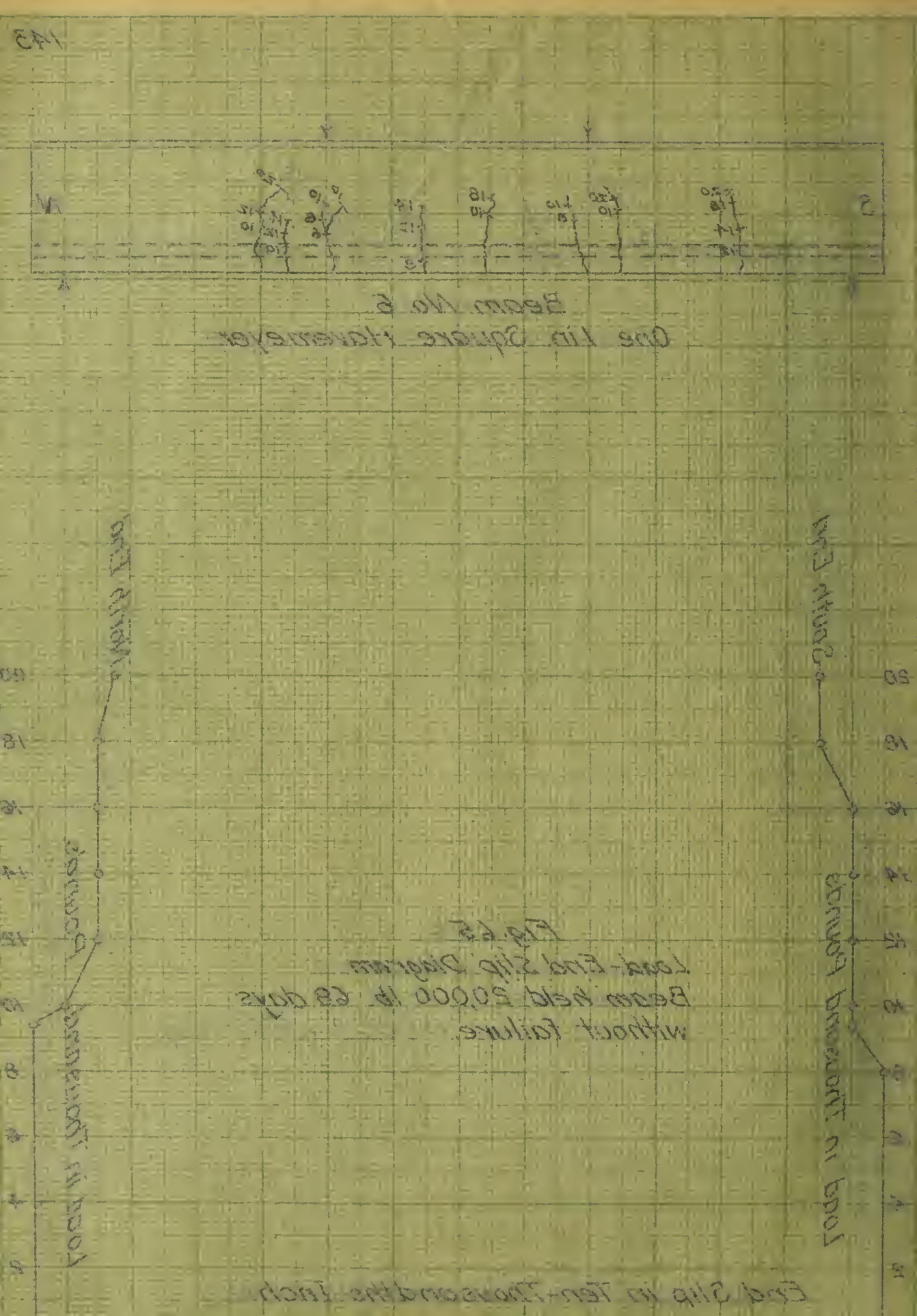
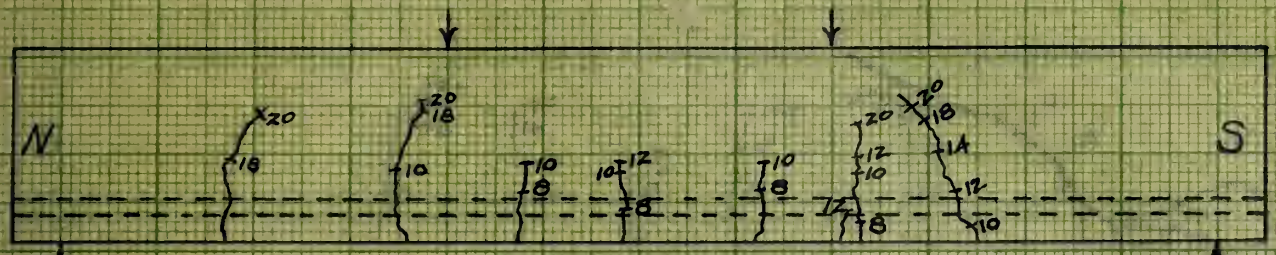
EUGENE DIETZGEN CO. CHICAGO NEW YORK





Beam No. 7.
One 1 in. Twisted Square.

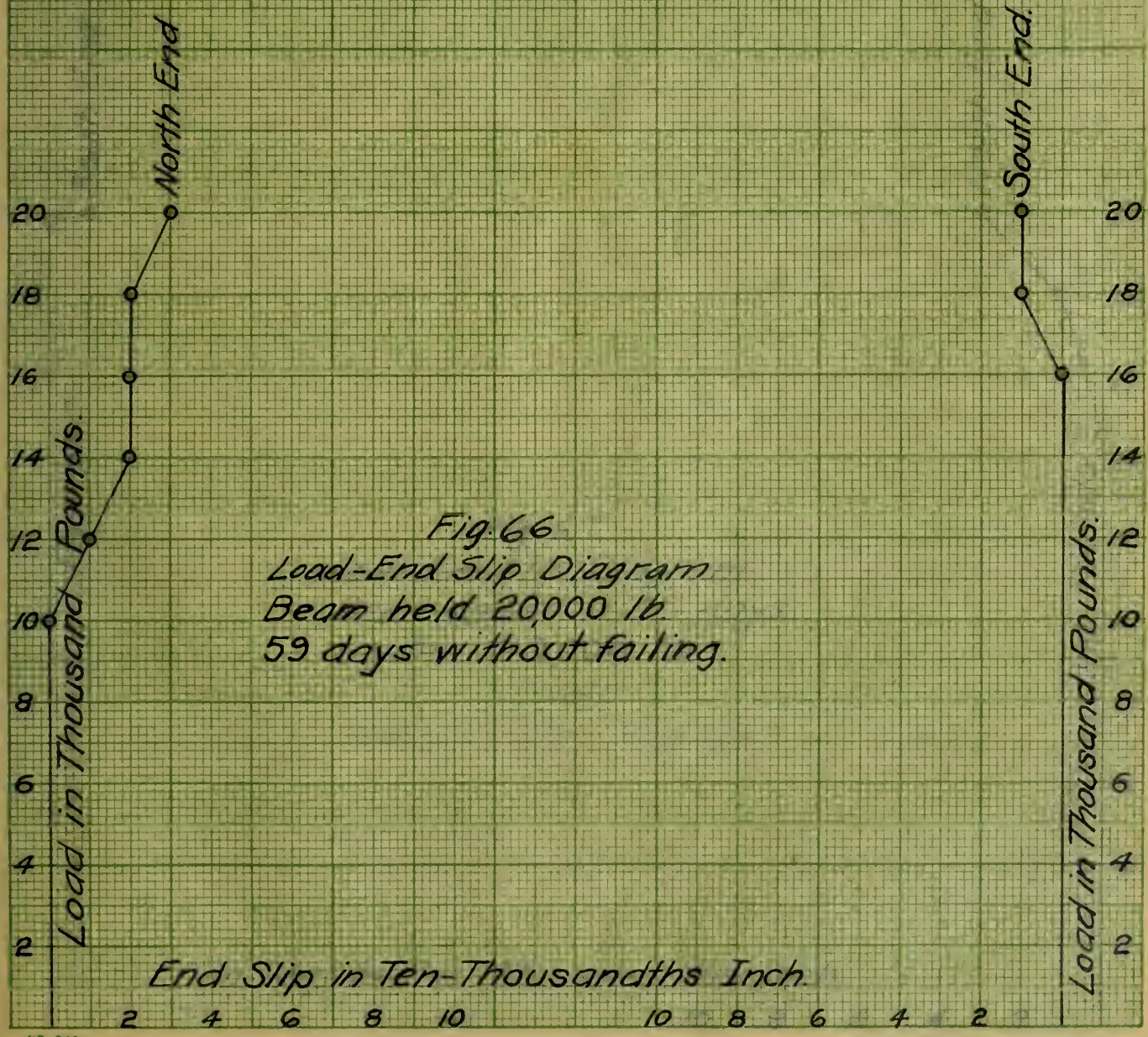
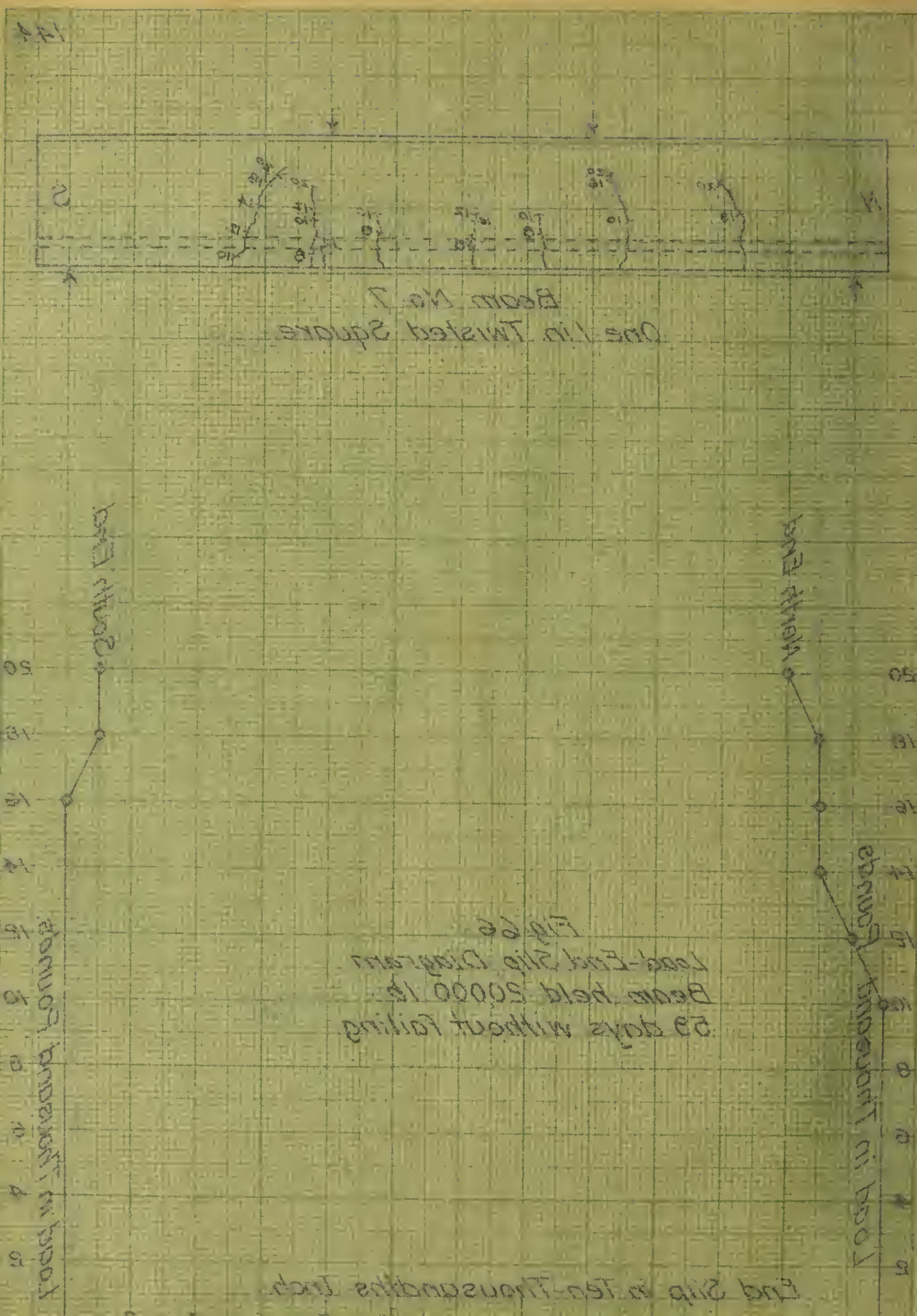
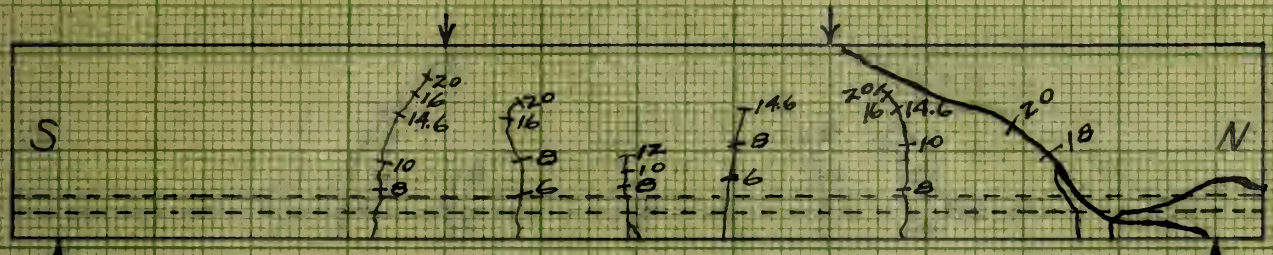


Fig. 66
Load-End Slip Diagram
Beam held 20,000 lb.
59 days without failing.

NO 346
EUGENE D. ETZGEN CO. CHICAGO NEW YORK





Beam No. 8.
One 1 in. Twisted Square.

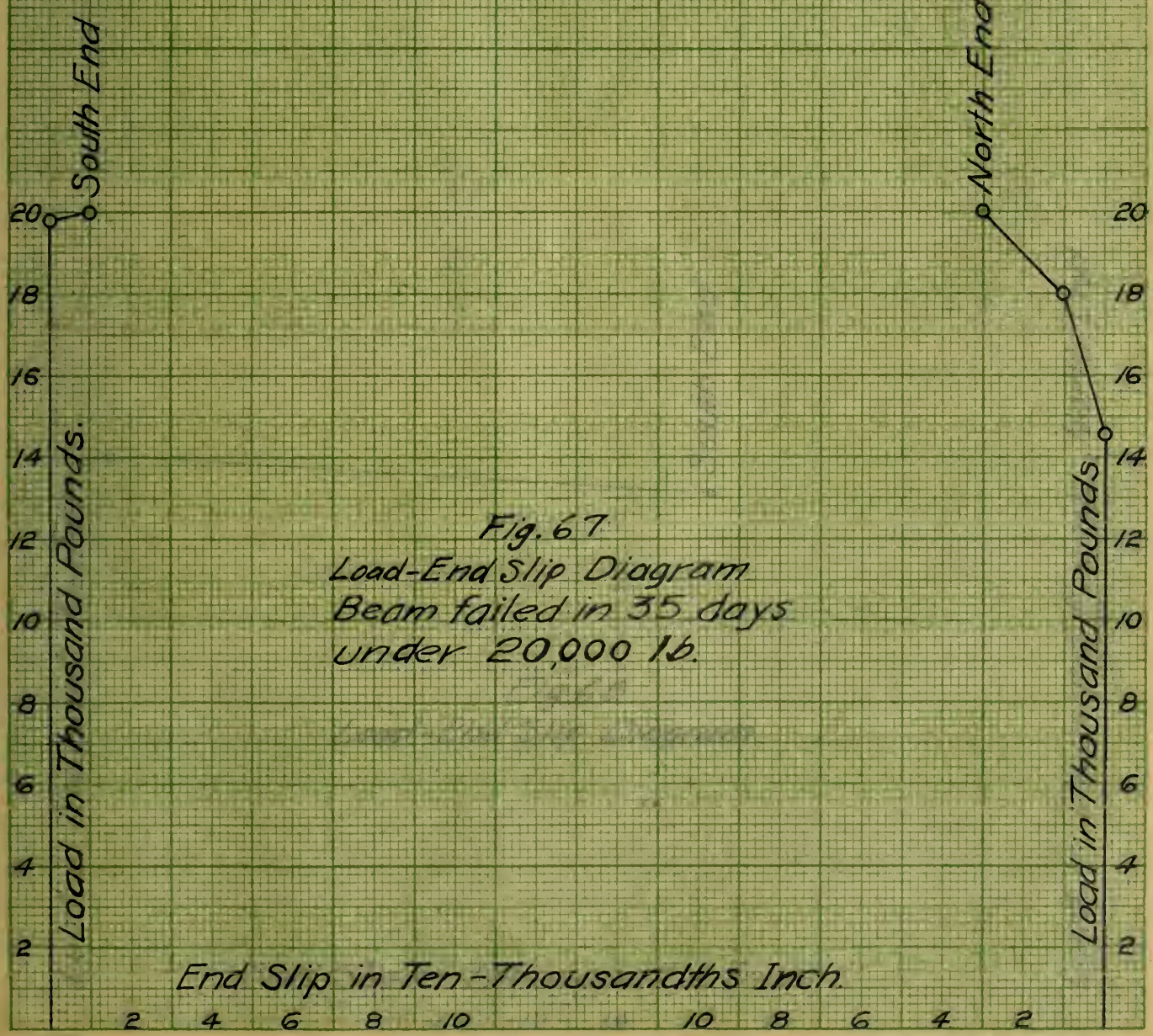


Fig. 67
Load-End Slip Diagram
Beam failed in 35 days
under 20,000 lb.

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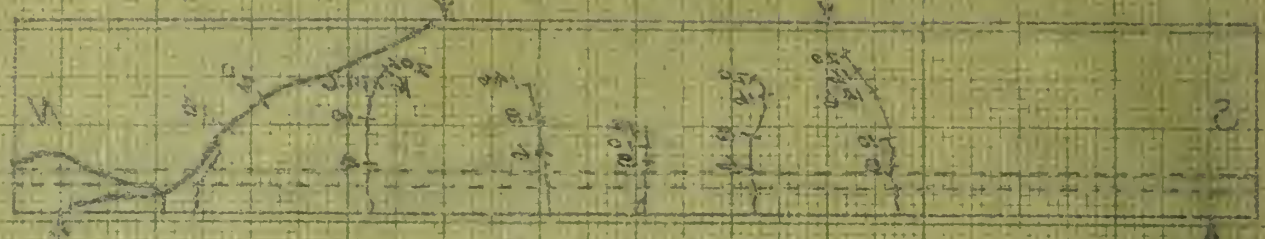
EUGENE D ETZEN CO CHICAGO-NEW YORK



Beam No. 3
One 1 in Twisted Square

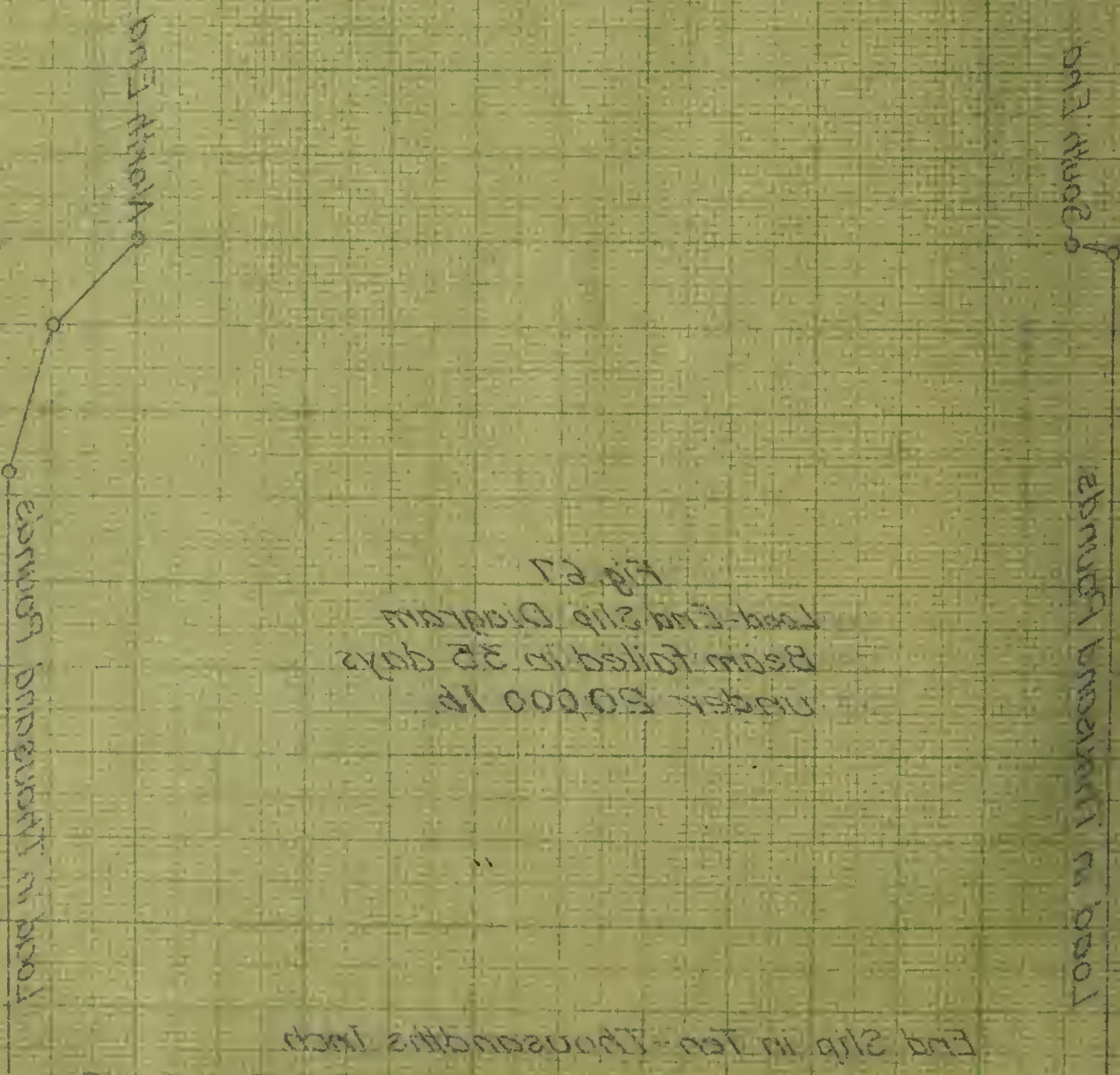
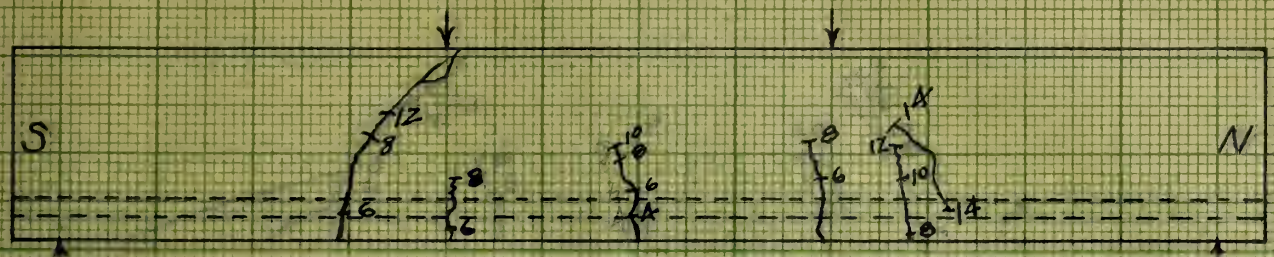


Fig. 67
Load-Time Slip Diagram
Beam Failed in 35 days
under 20,000 lb.

End Slip in Ten-Thousandths Inch



Beam No. S.C. 1.
One 1 in. Plain Round.

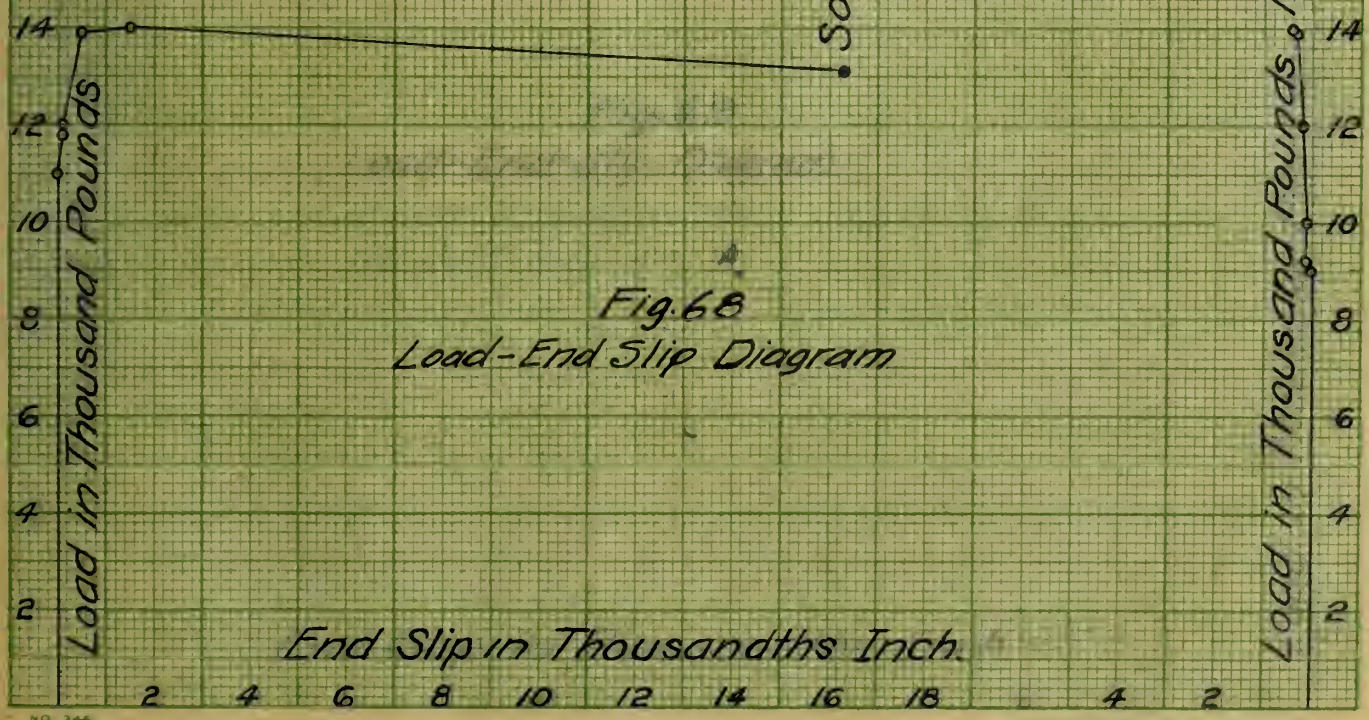
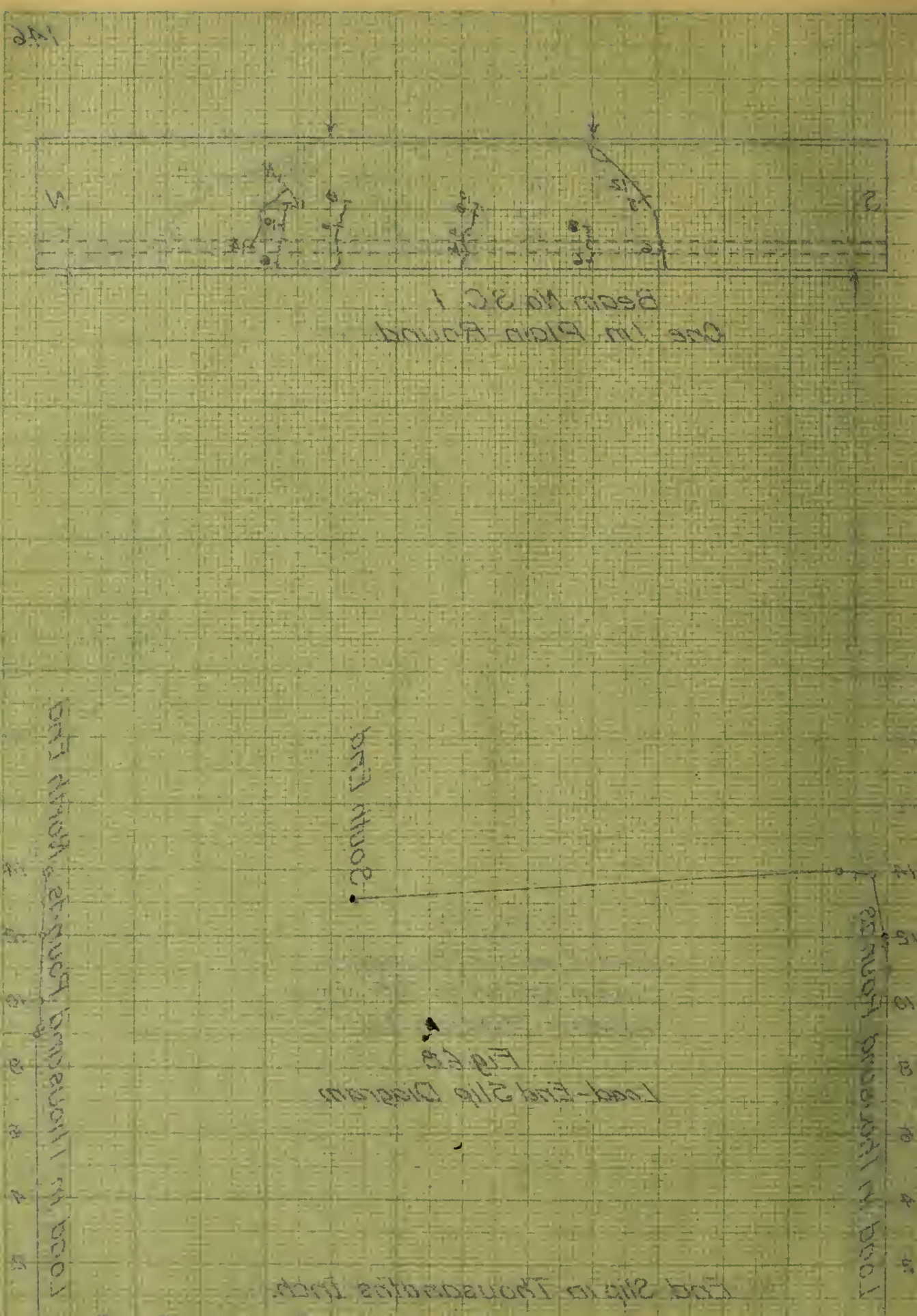
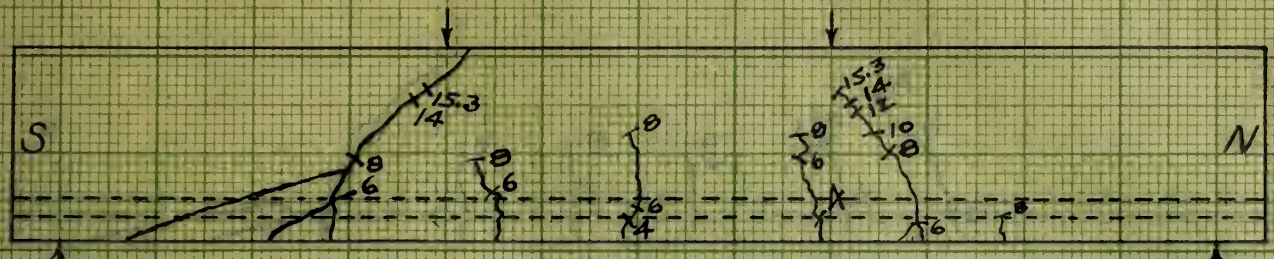


Fig. 68
Load-End Slip Diagram

NO 346
EUGENE D. ETZGEN CO. CHICAGO-NEW YORK



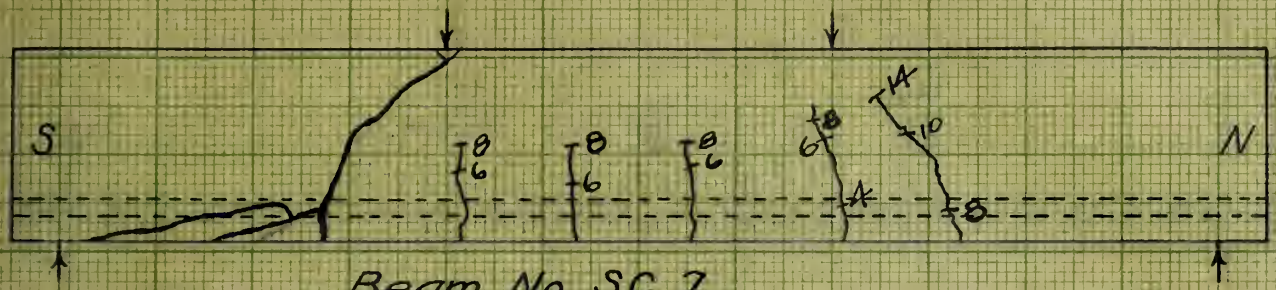


Beam No. SC 4.
One 1 in. Plain Round.

Fig. 69
Load-End Slip Diagram

NO 346
EUGENE D ETZGEN CO CHICAGO-NEW YORK

Fig. 65
Load-End Slip Diagram



Beam No. SC 7.
One 1 in. Plain Round.

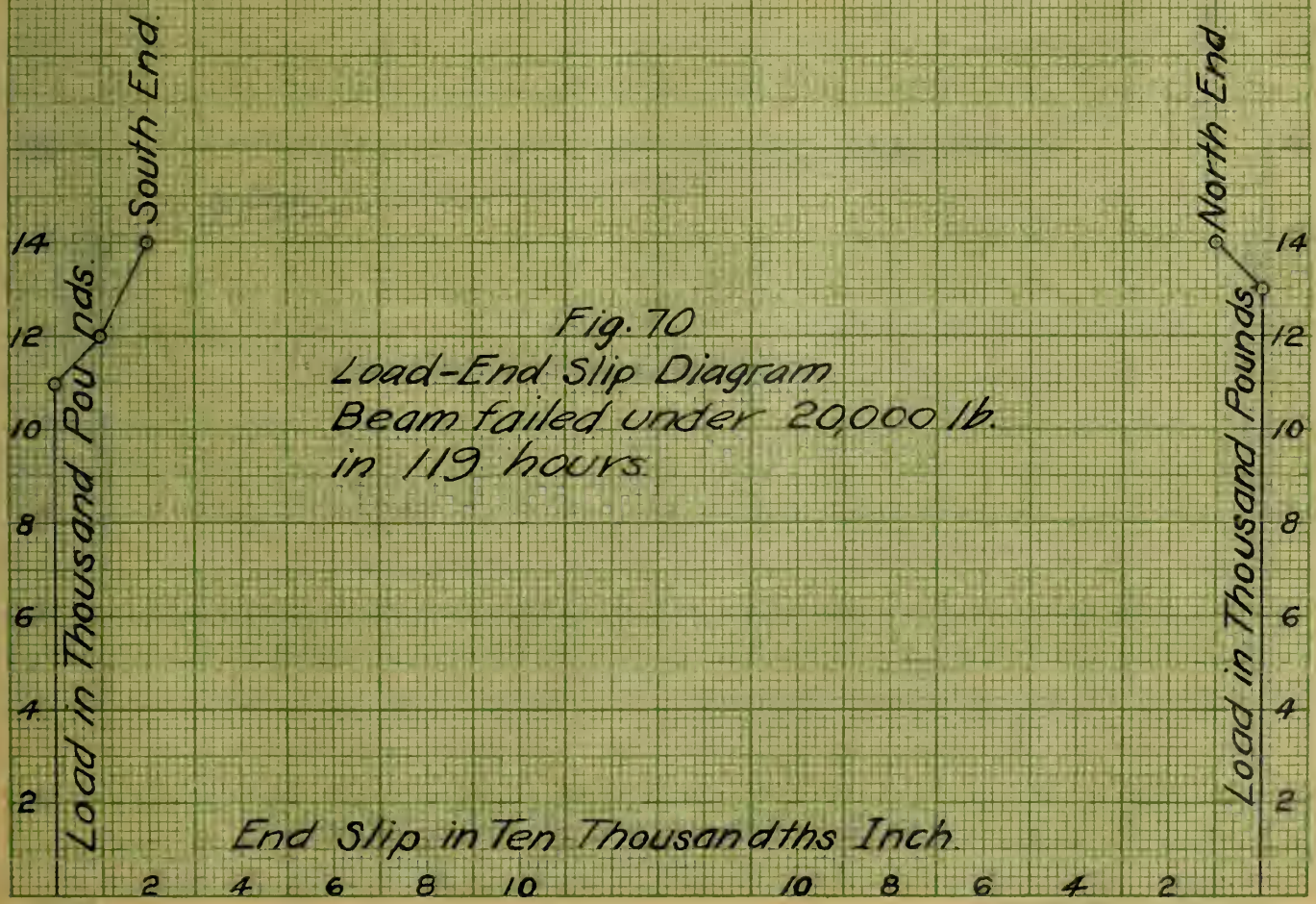
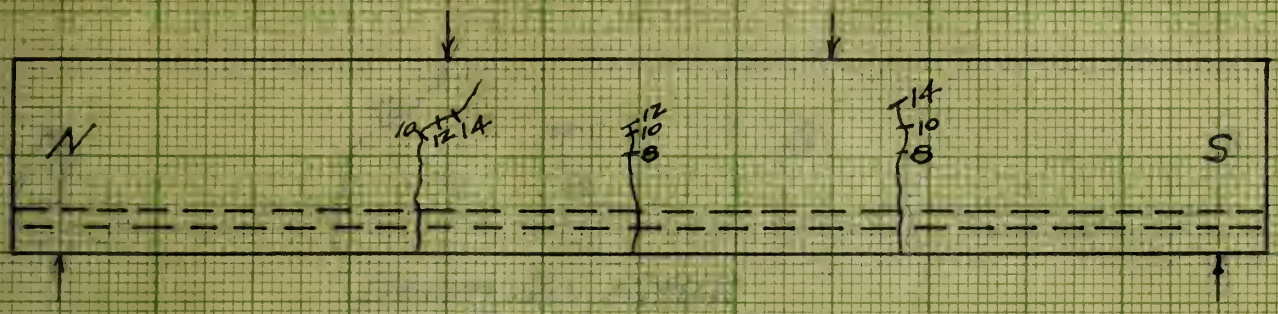


Fig. 70
Load-End Slip Diagram
Beam failed under 20,000 lb.
in 119 hours.

NO 346
EUGENE D ETZGEN CO CHICAGO-NEW YORK



Beam No. 1081.1
One 1in. Plain Round Bar

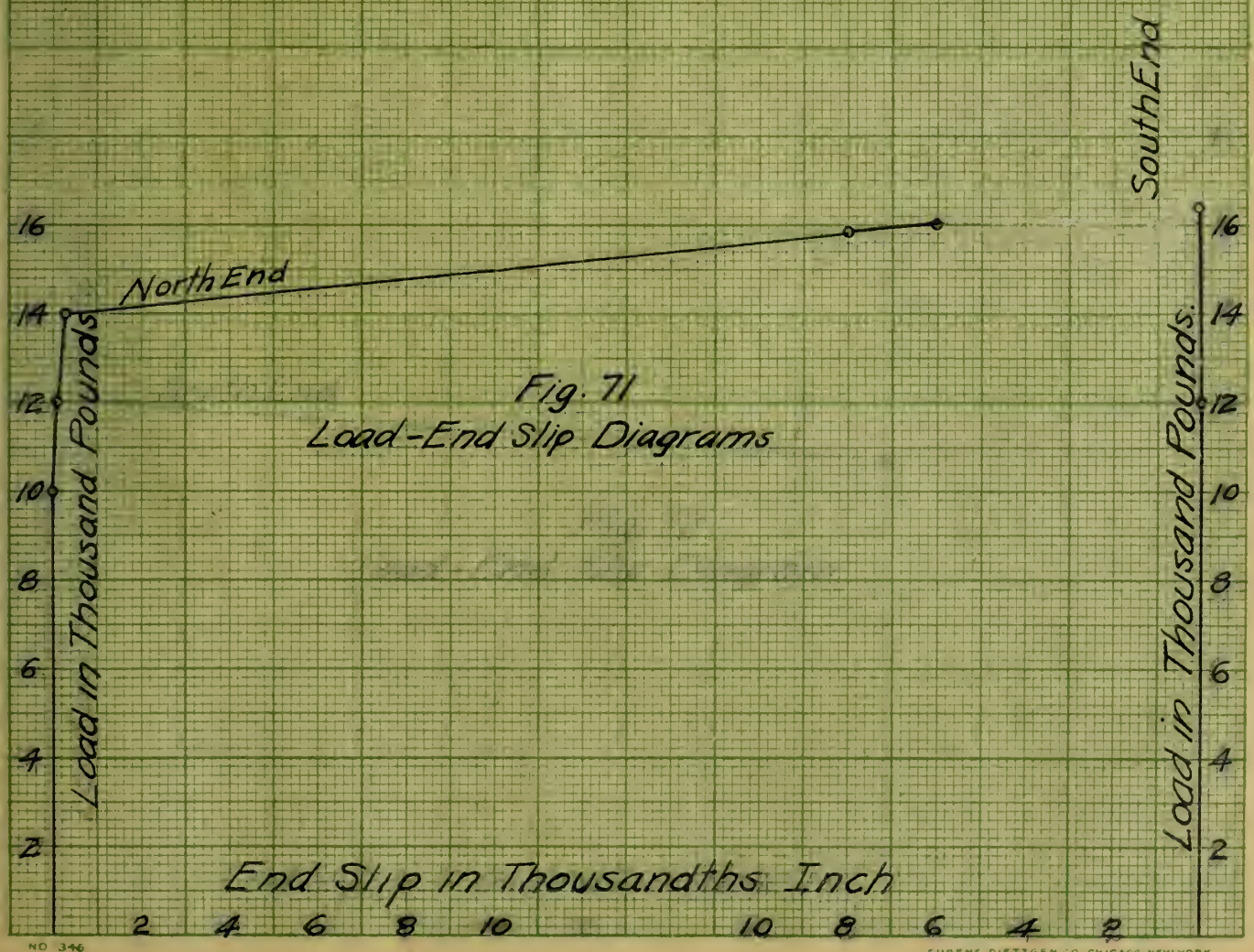
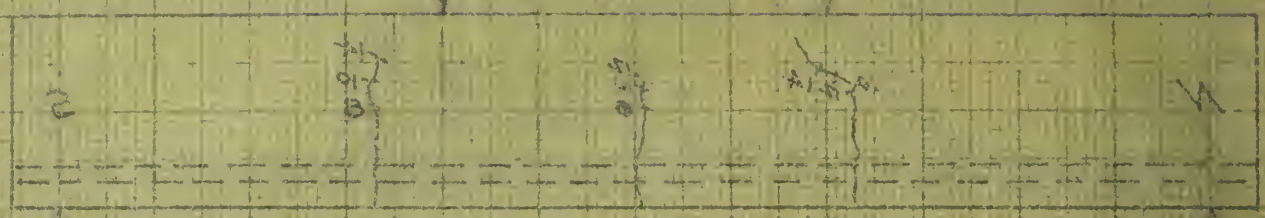
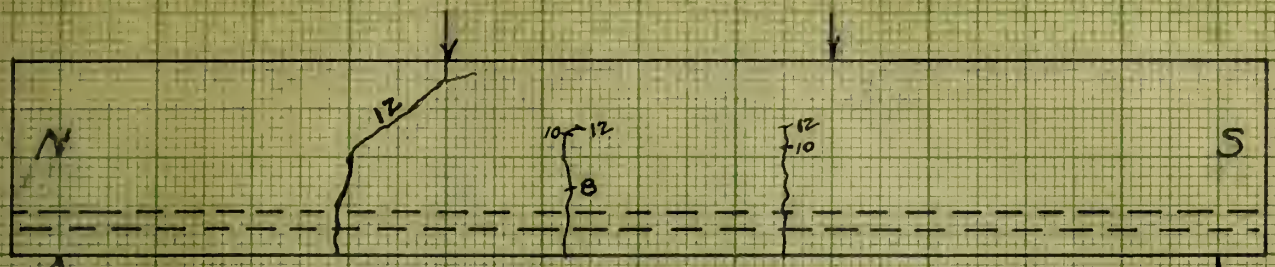


Fig. 71
Load-End Slip Diagrams

NO 346
EUGENE DIETZGEN CO. CHICAGO-NEW YORK





Beam No. 1081.2
One 1 in. Plain Round

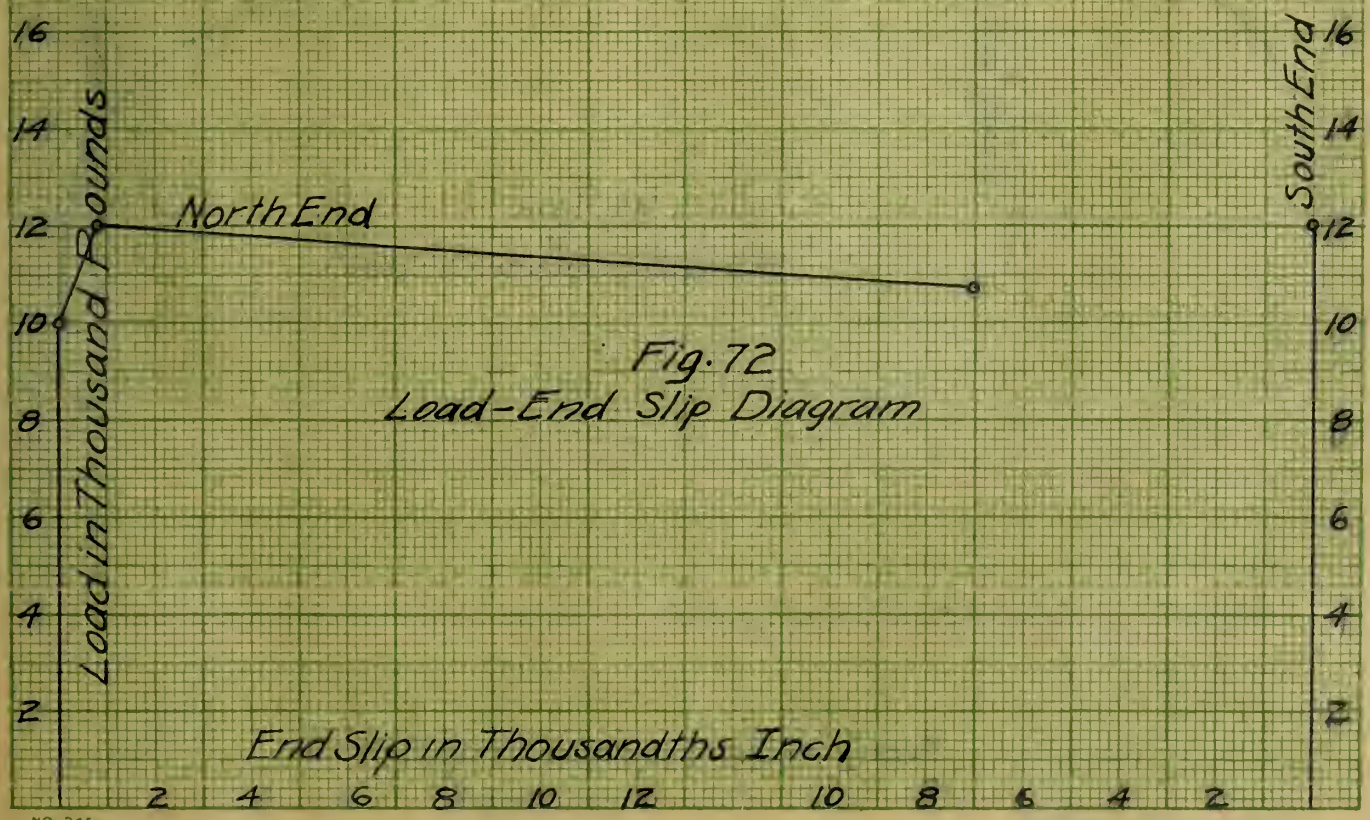
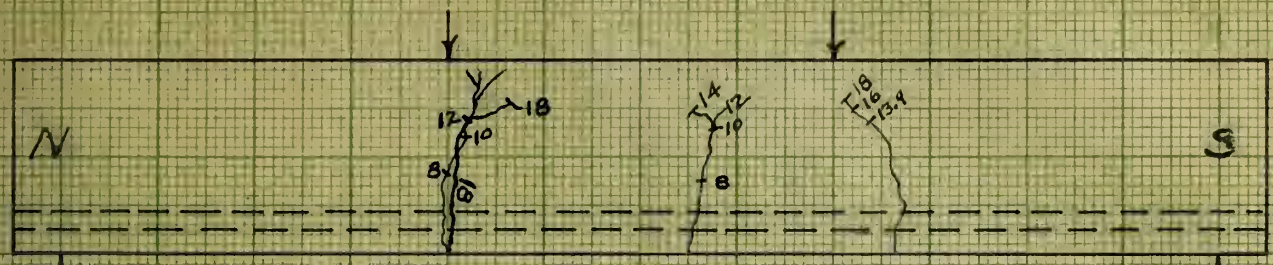


Fig. 72
Load-End Slip Diagram

NO 346
EUGENE D ETZGEN CO CHICAGO-NEW YORK



Beam No. 1081.3
One 1 in. Plain Round

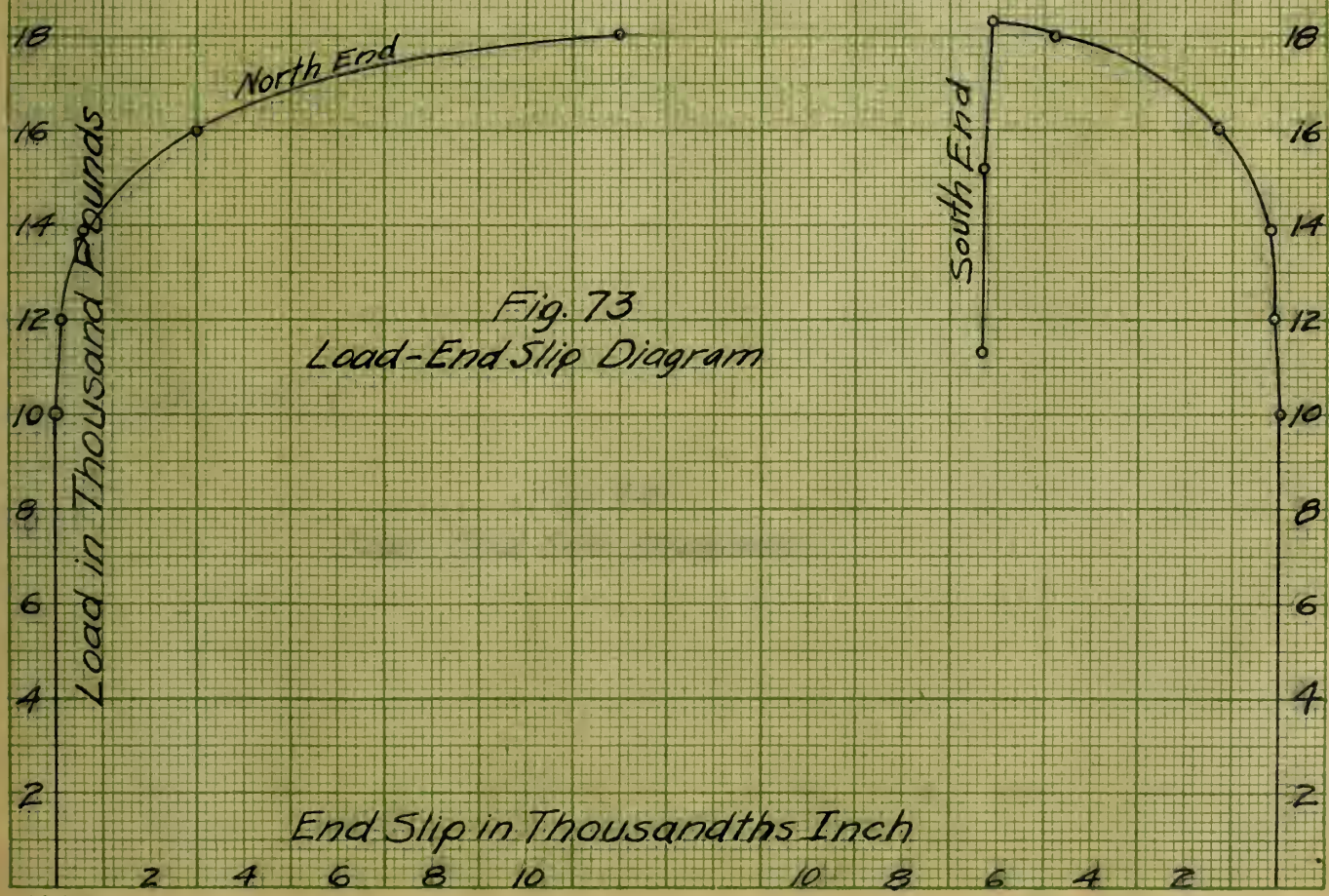


Fig. 73
Load-End Slip Diagram

EUGENE D ETZGEN CO CHICAGO-NEW YORK

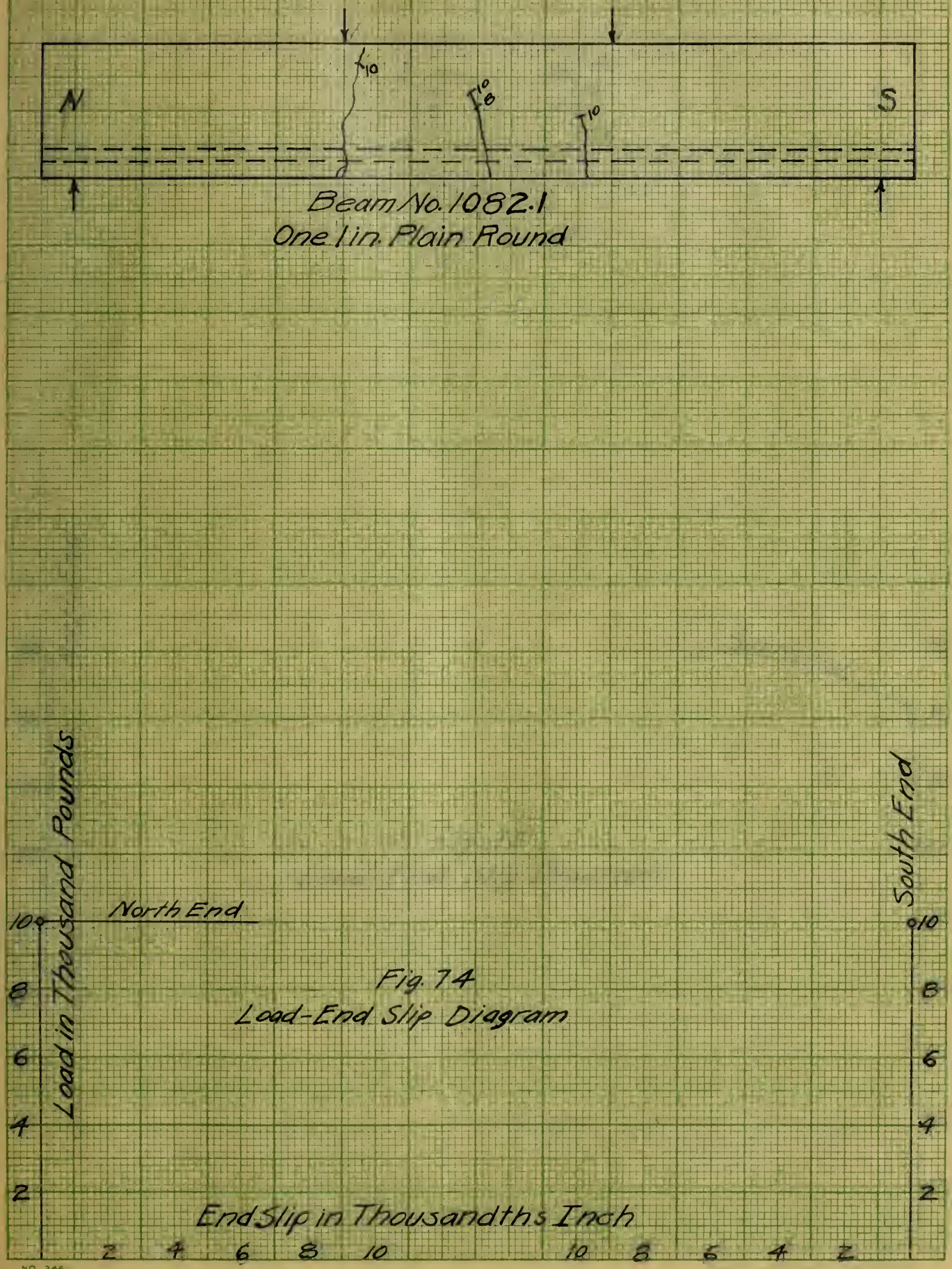
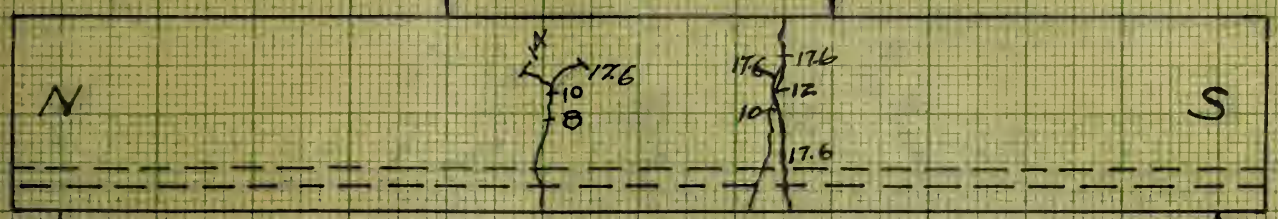


Fig. 74
Load-End Slip Diagram

NO 346
EUGENE C ETZGEN CO CHICAGO NEW YORK



Beam No. 1082.2
One 1 in. Plain Round

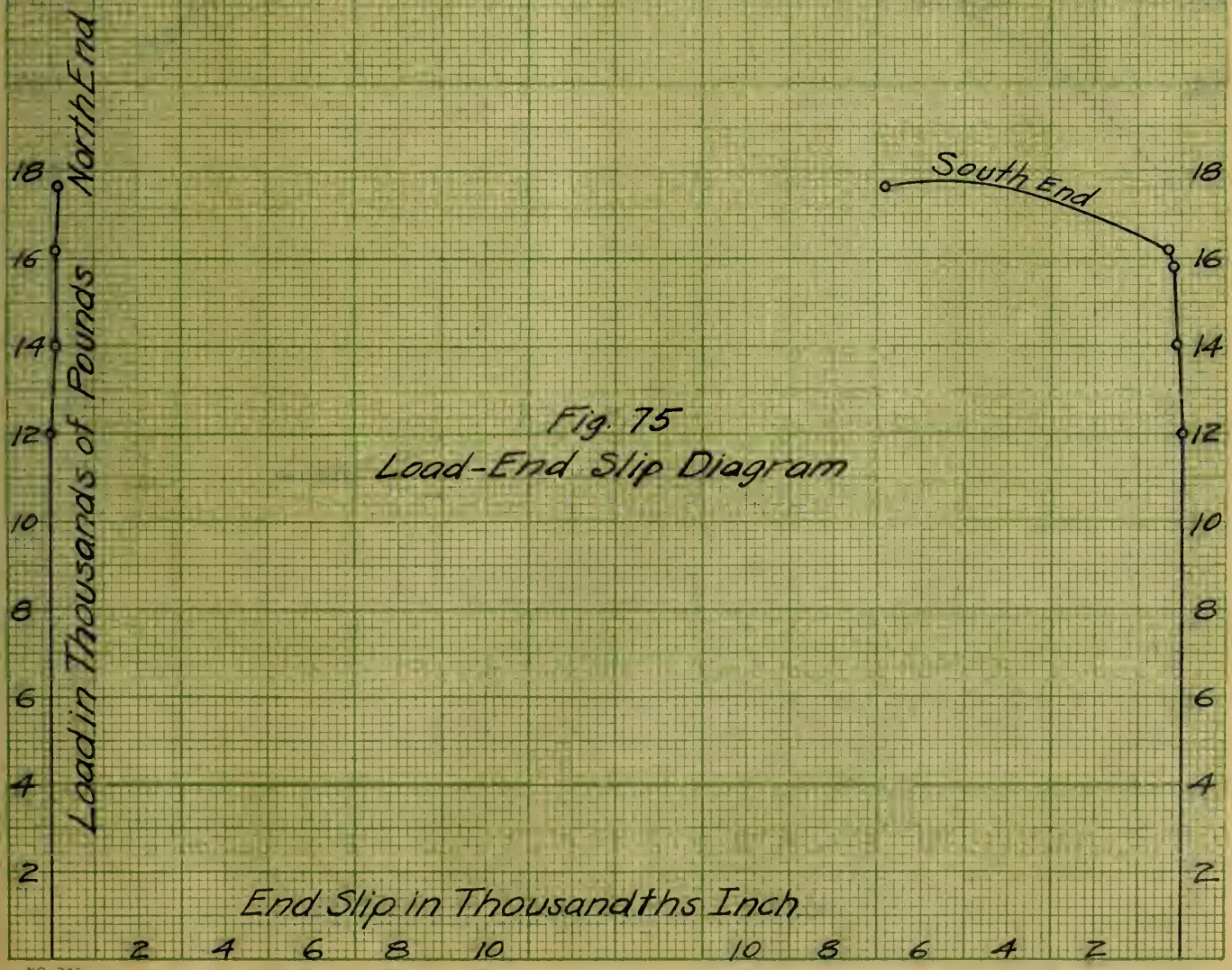
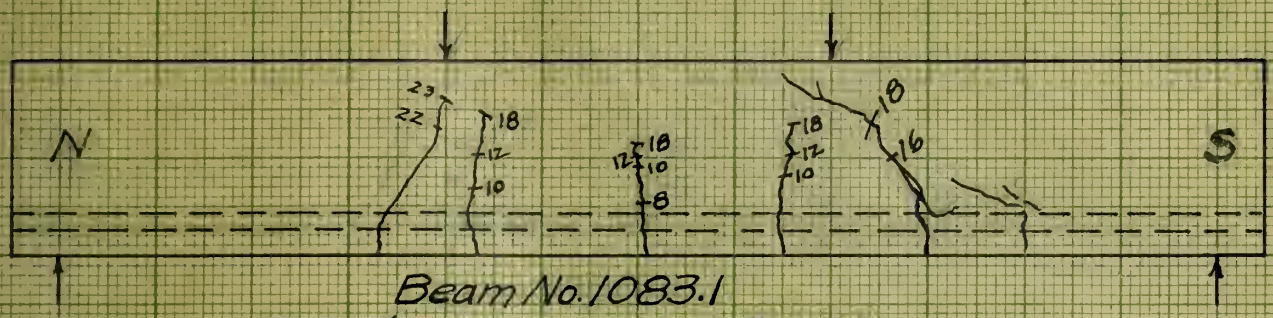


Fig. 75
Load-End Slip Diagram

NO 346
EUGENE C. ETZGEN CO. CHICAGO NEW YORK



Beam No. 1083.1
One 1/8 in. Corrugated Round

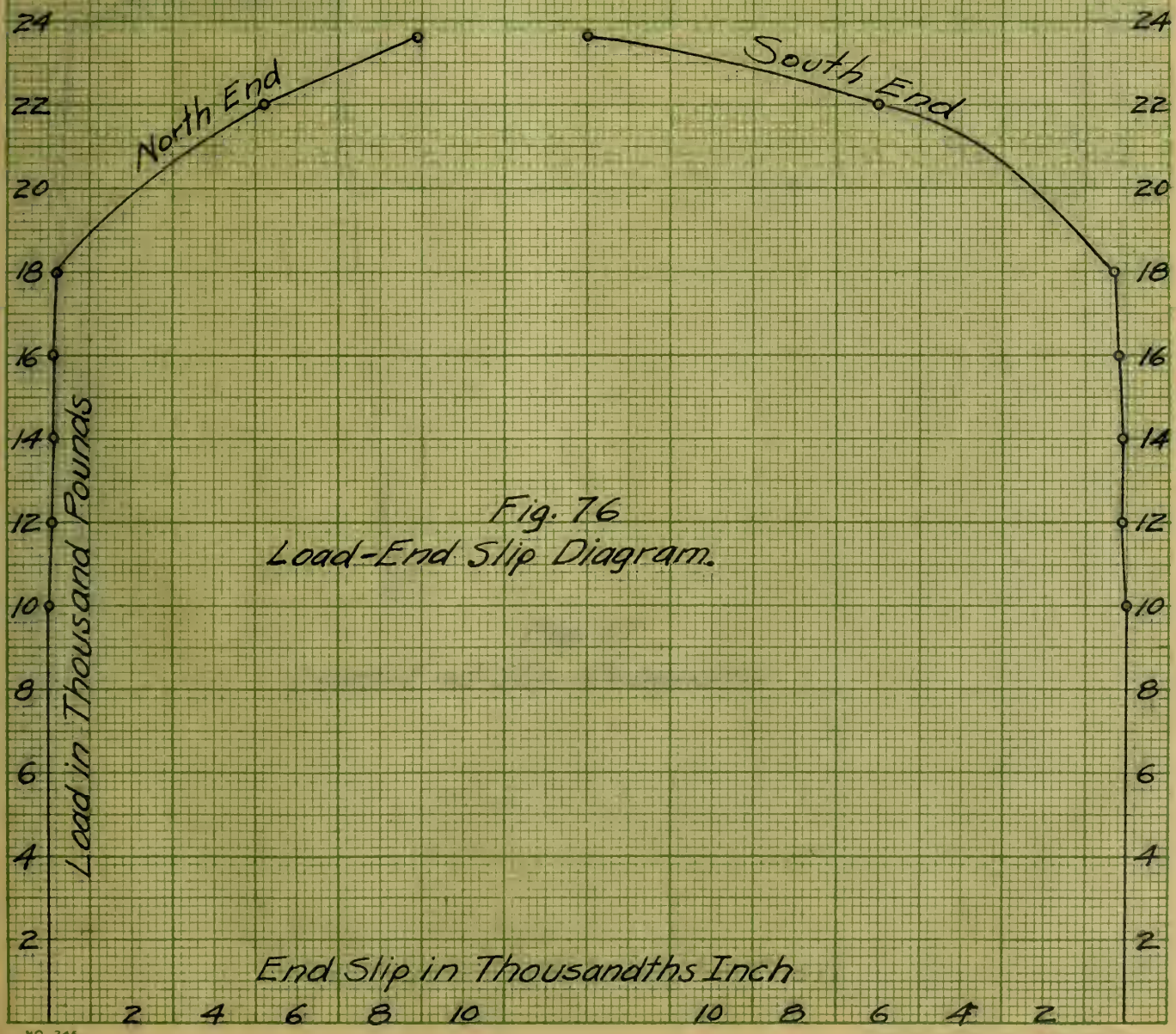
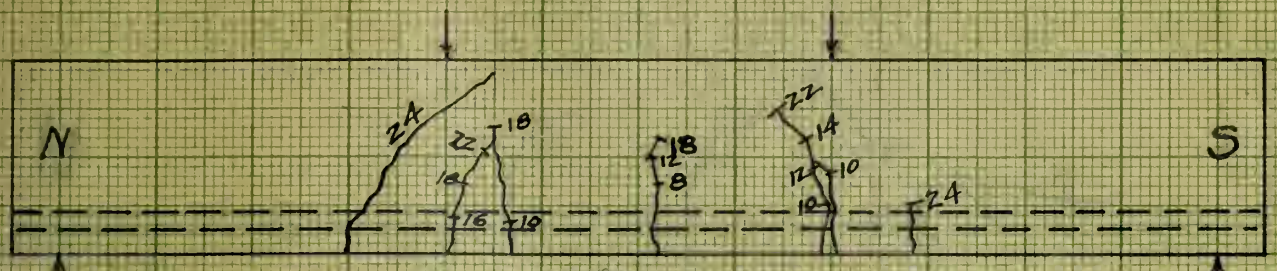


Fig. 76
Load-End Slip Diagram.

NO 346
EUGENE DIETZGEN CO CHICAGO-NEW YORK



Beam 1083.2
One 1/8 in. Corrugated Round

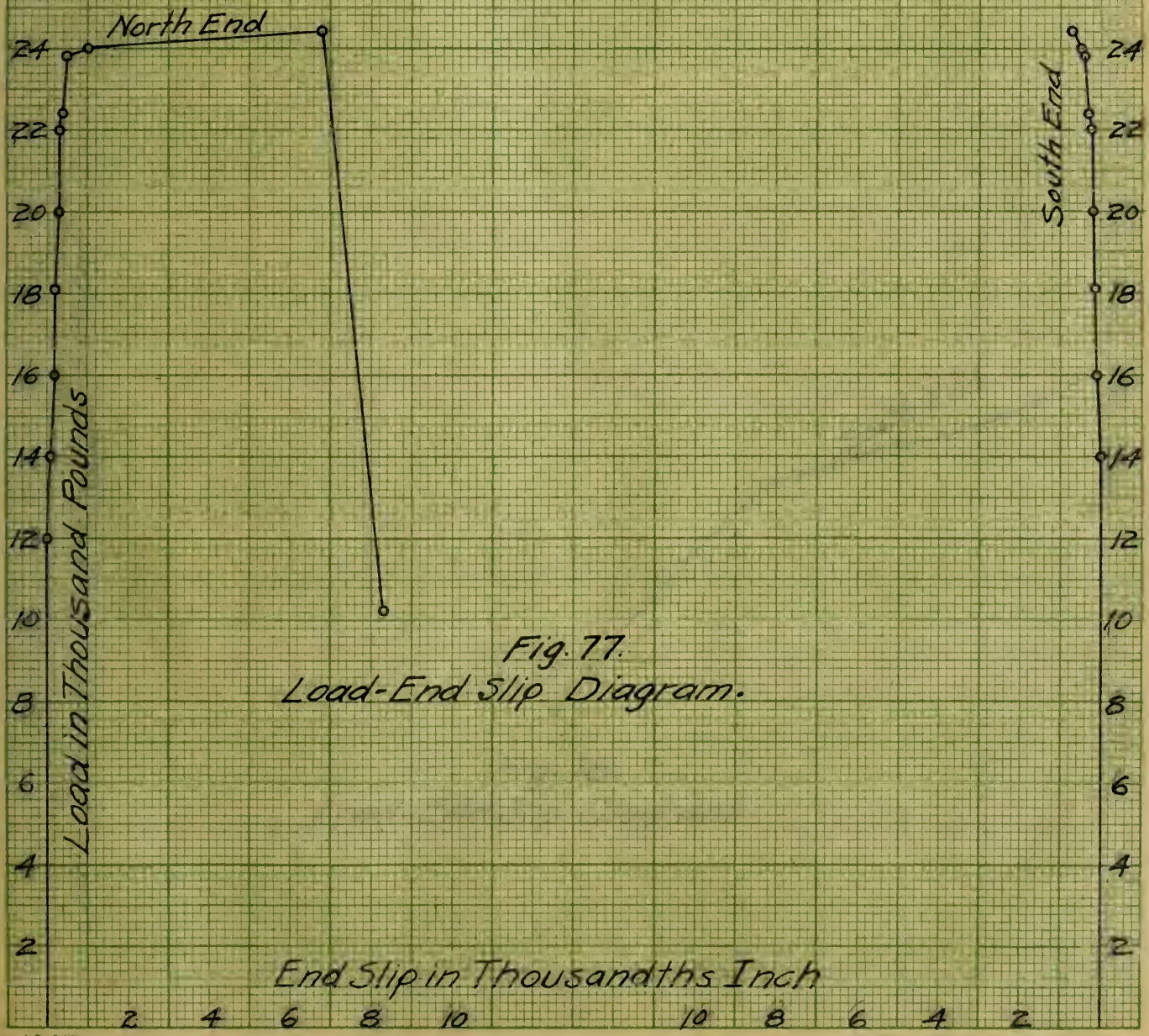
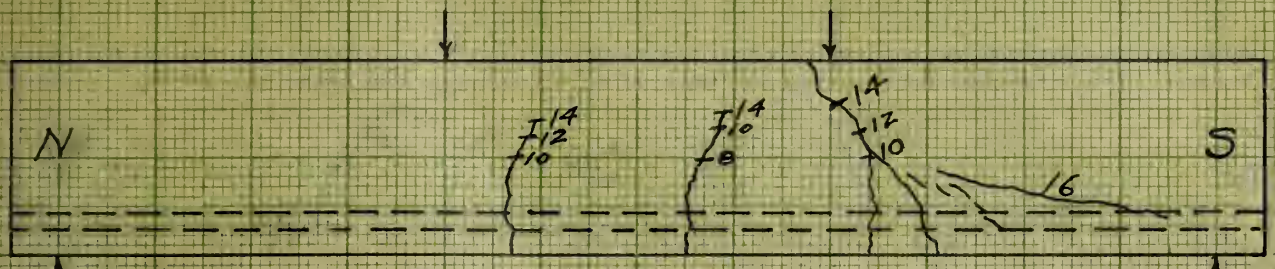


Fig. 77.
Load-End Slip Diagram.

NO 346
EUGENE DIETZGEN CO CHICAGO-NEW YORK



Beam No. 1084.1
One 1½ in. Corrugated Round

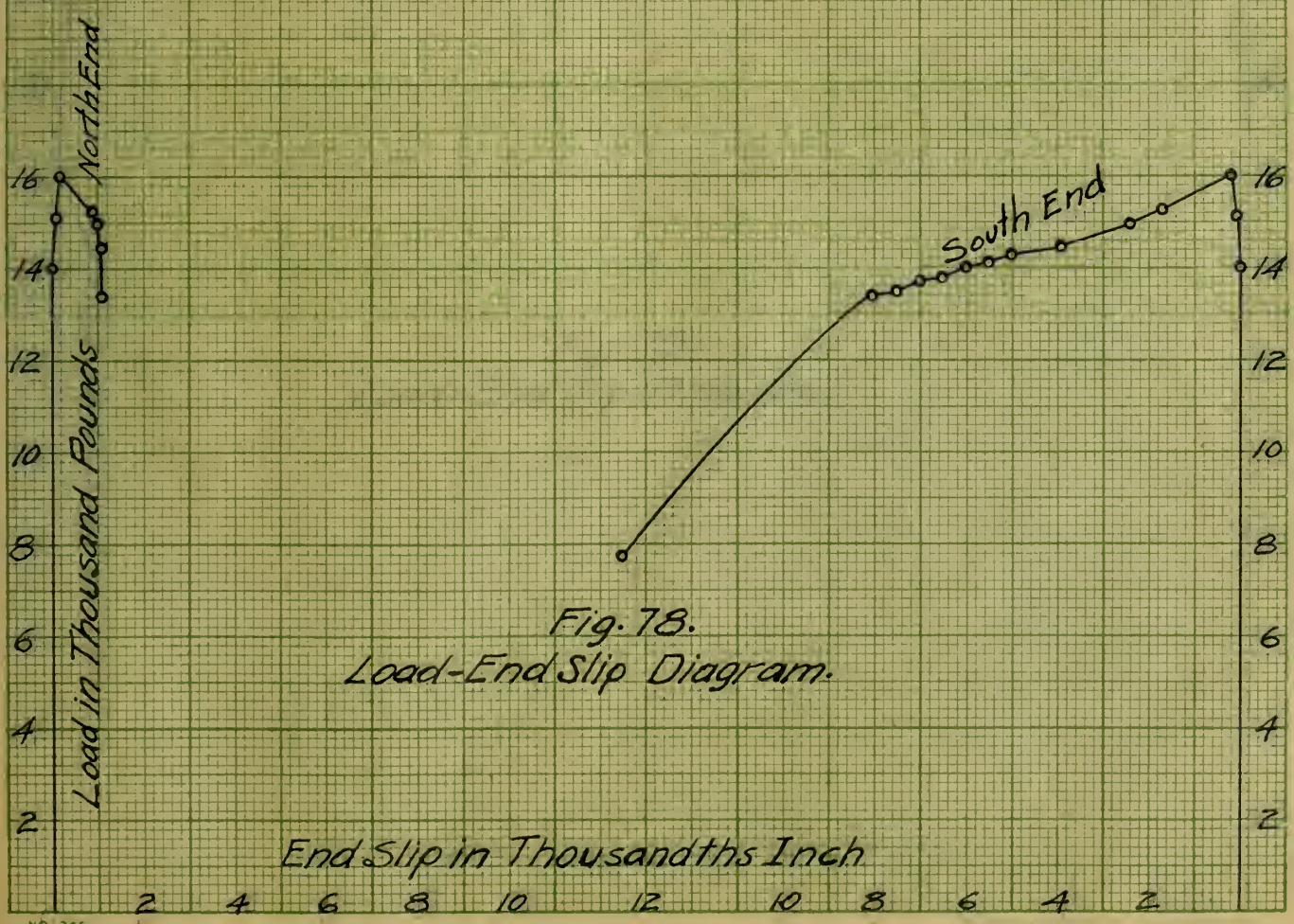
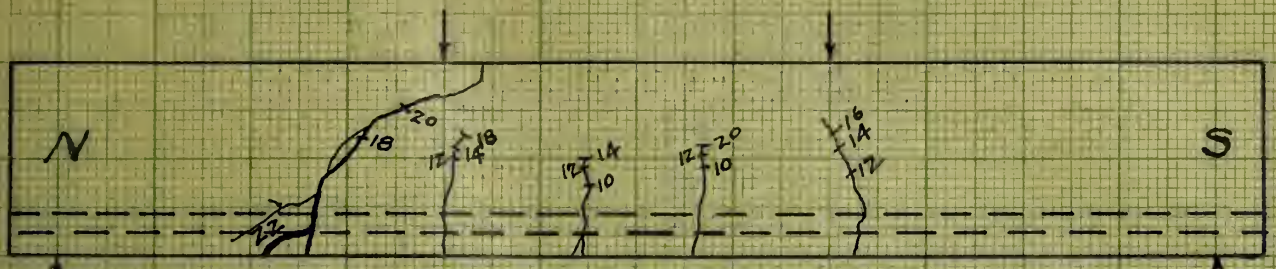


Fig. 78.
Load-End Slip Diagram.

EUGENE DIETZGEN CO. CHICAGO-NEW YORK



Beam No. 1084-2
One 1⅛ in. Corrugated Round

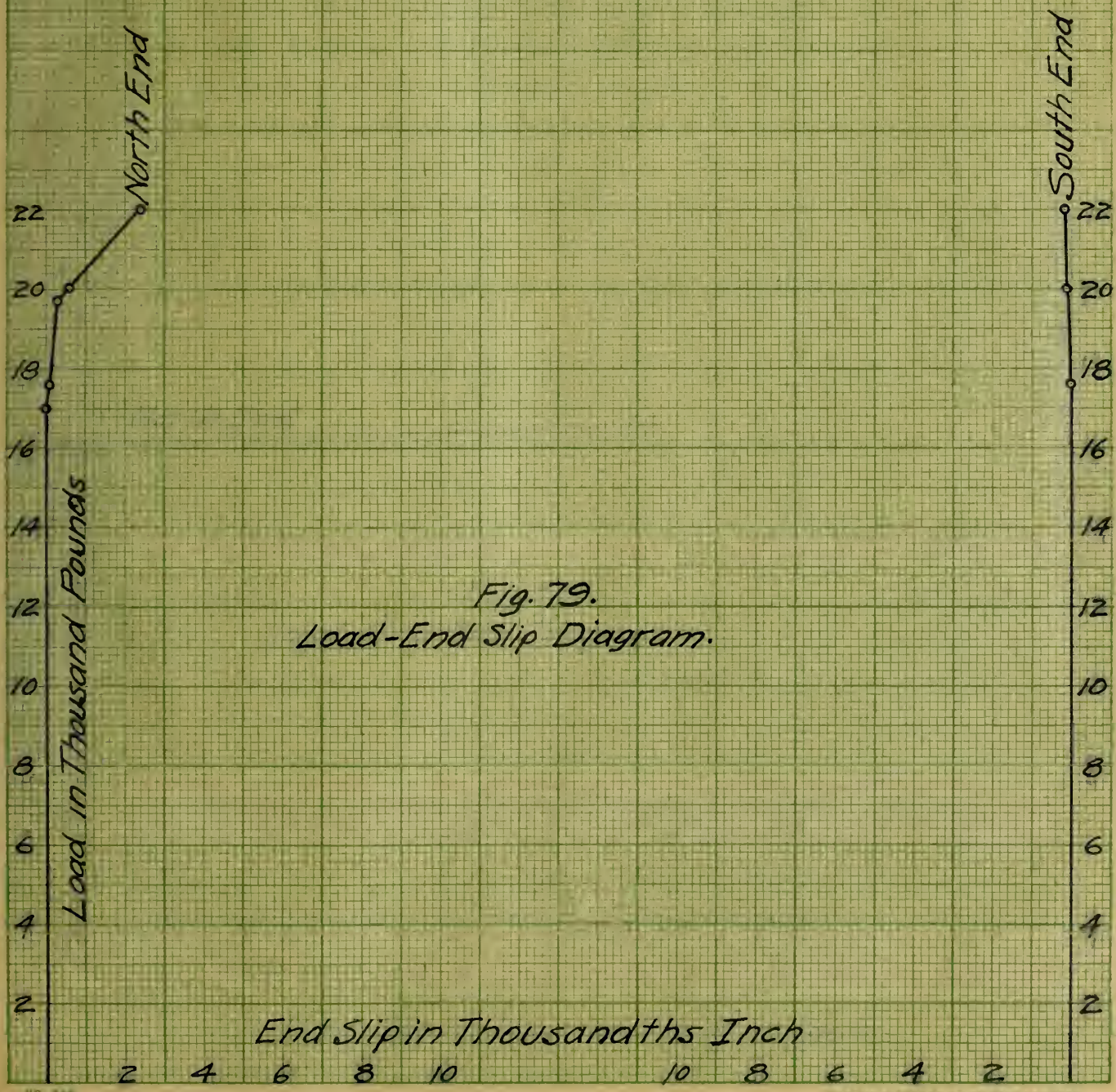
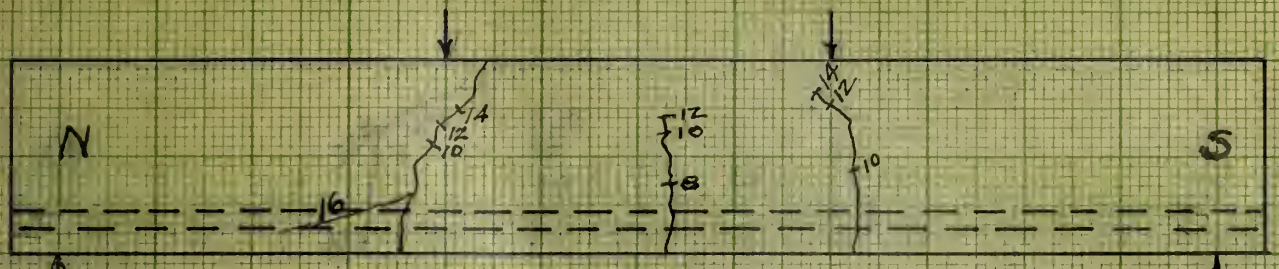


Fig. 79.
Load-End Slip Diagram.

NO 346
EUGENE DIETZGEN CO. CHICAGO NEW YORK



Beam 1085.1
One 1 in. Plain Round

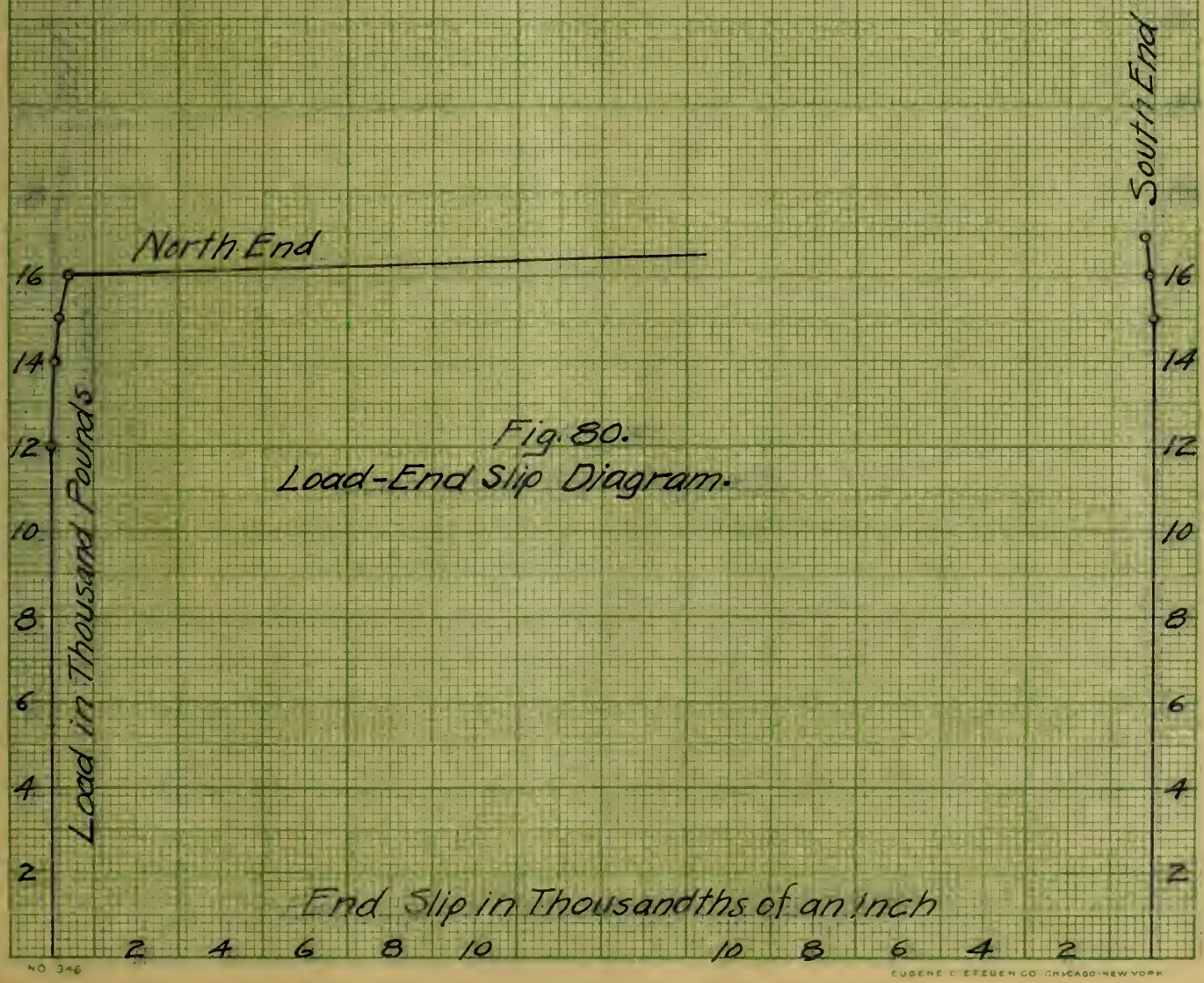
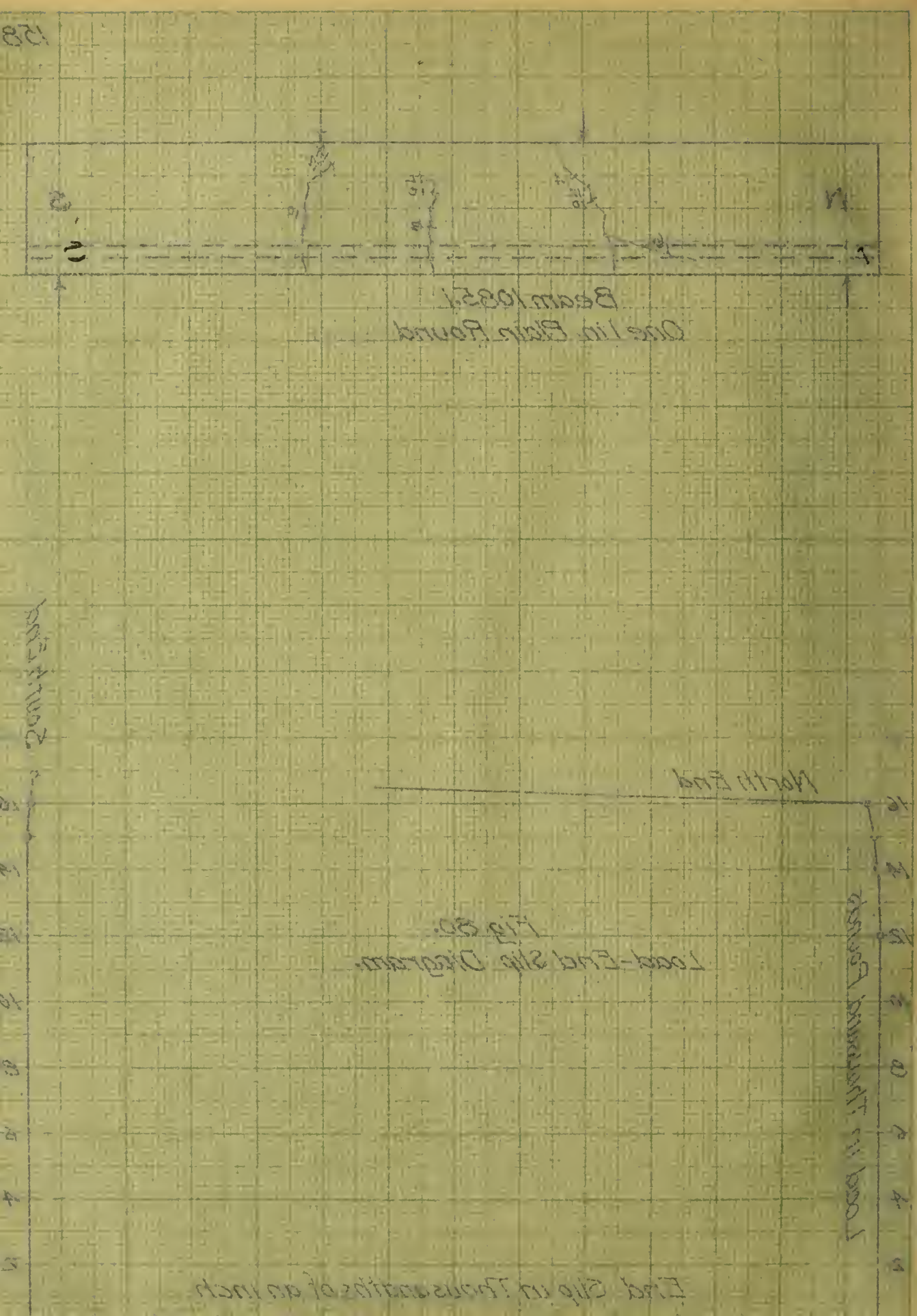


Fig. 80.
Load-End Slip Diagram.

NO 346
EUGENE C. EITZEN CO. CHICAGO-NEW YORK



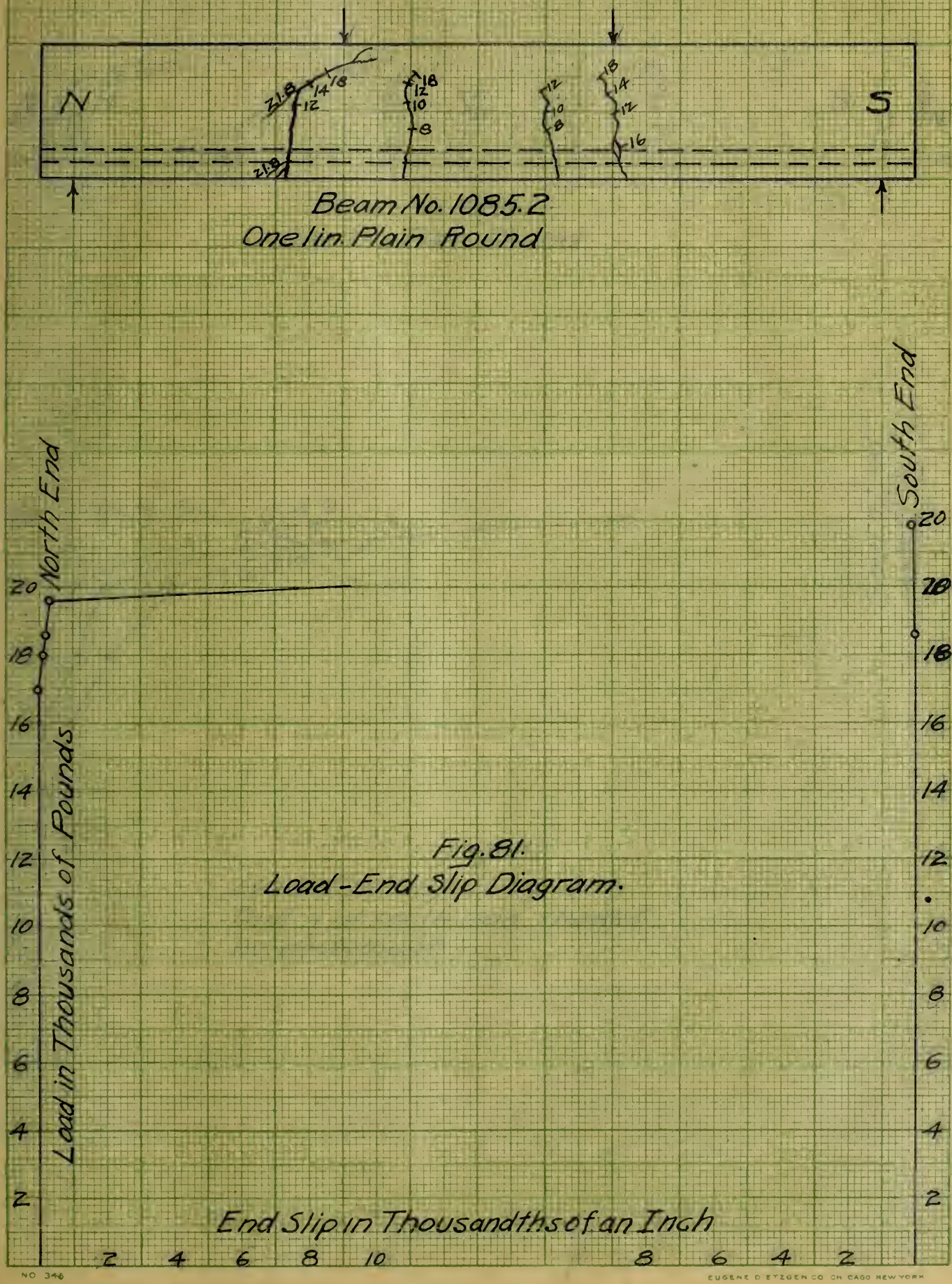
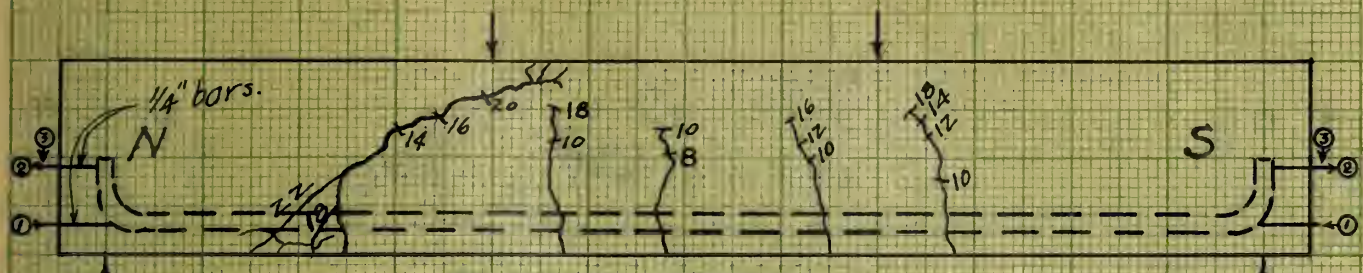


Fig. 81.
Load-End Slip Diagram.

NO 346
EUGENE DIETZGEN CO CHICAGO NEW YORK



Beam No. 1086.1
One 1 in. Plain Round

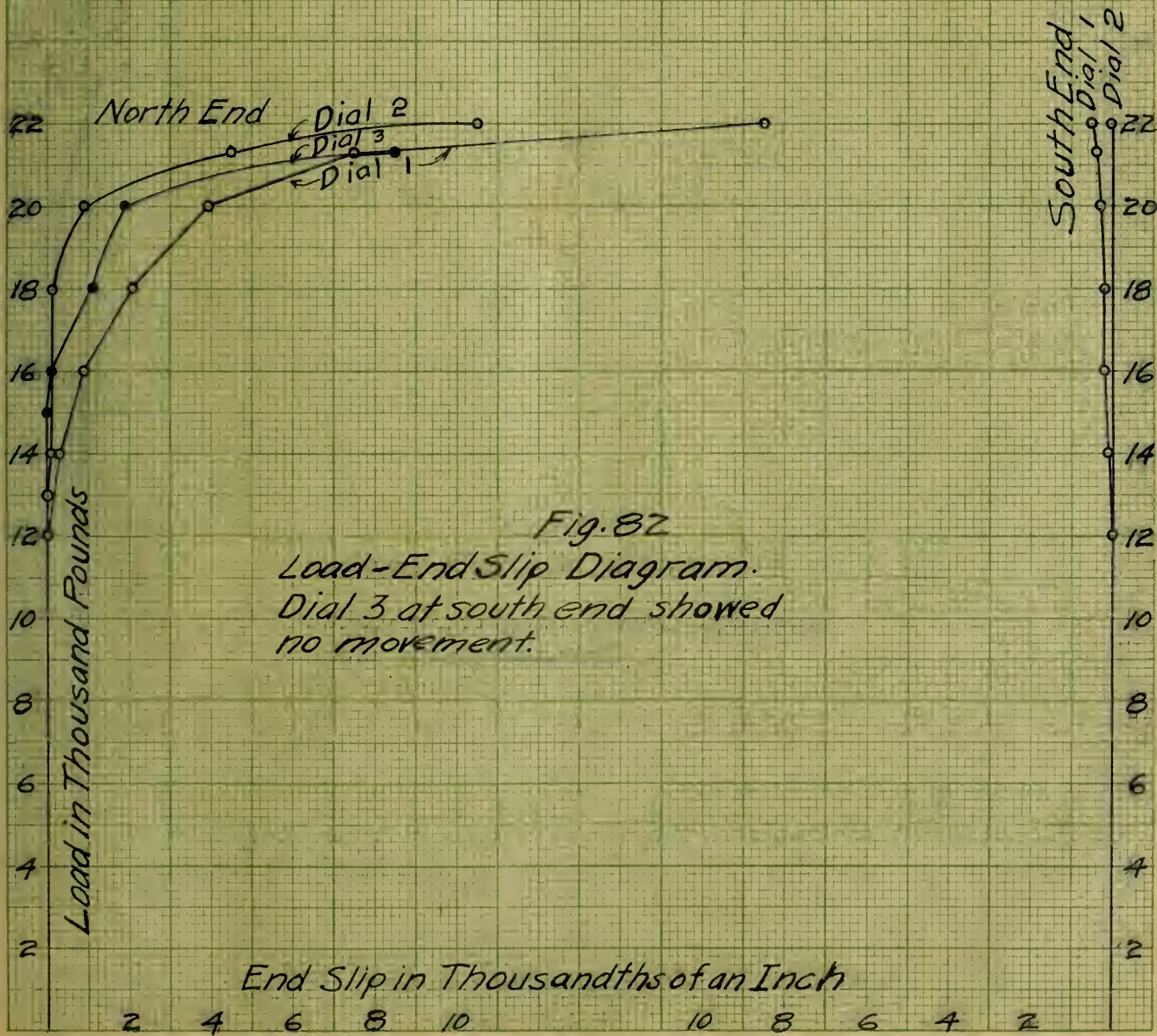


Fig. 82
Load-End Slip Diagram.
Dial 3 at south end showed no movement.

NO 346
EUGENE DIETZGEN CO. CHICAGO NEW YORK

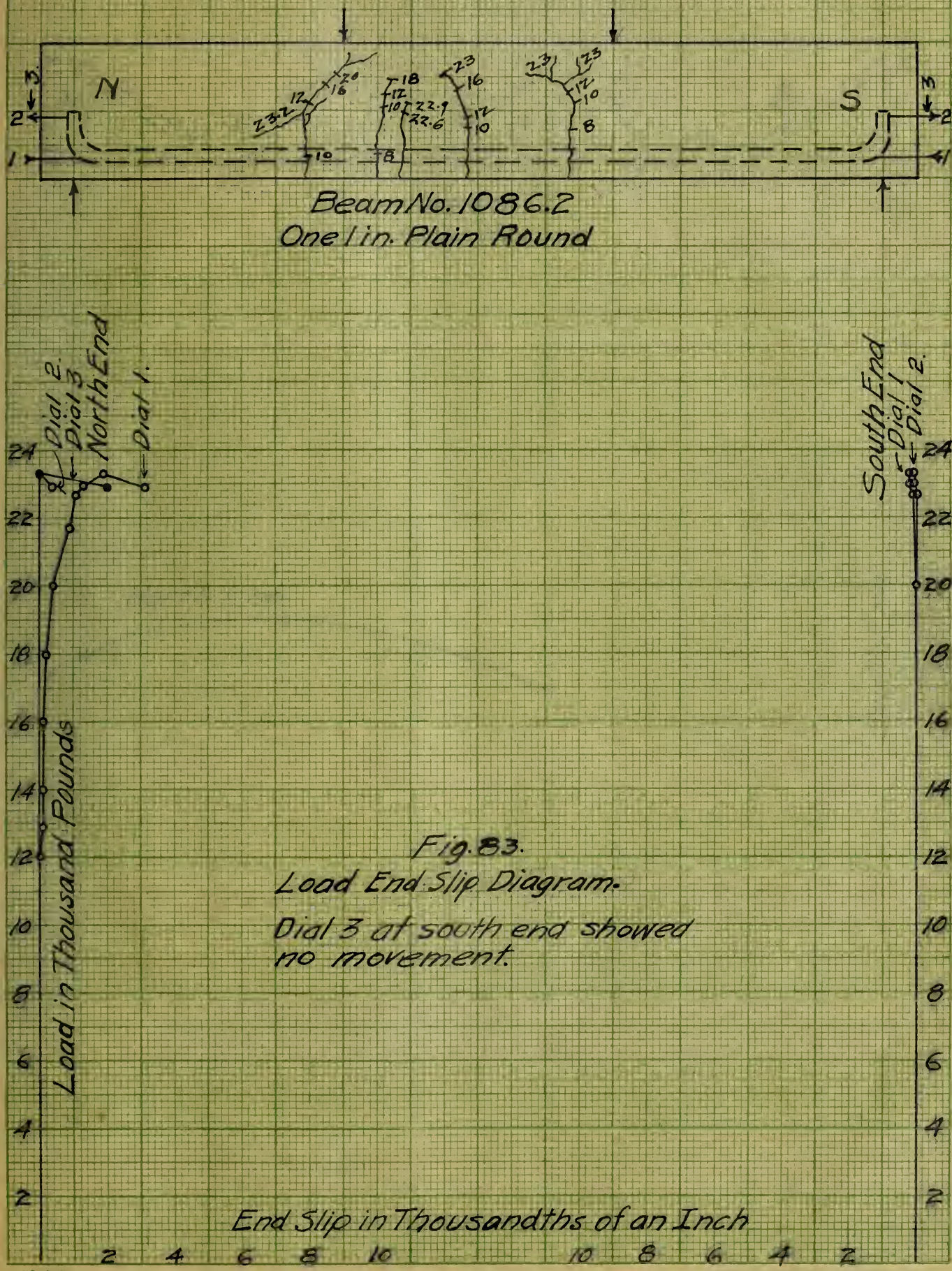
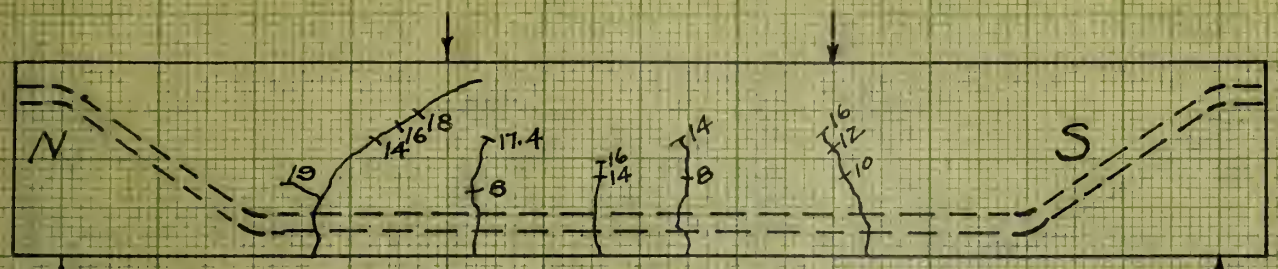


Fig. 83.
Load End Slip Diagram.
Dial 3 at south end showed no movement.

NO 346
EUGENE D ETZGEN CO CHICAGO NEW YORK



Beam No. 1087.2
One 1 in. Plain Round

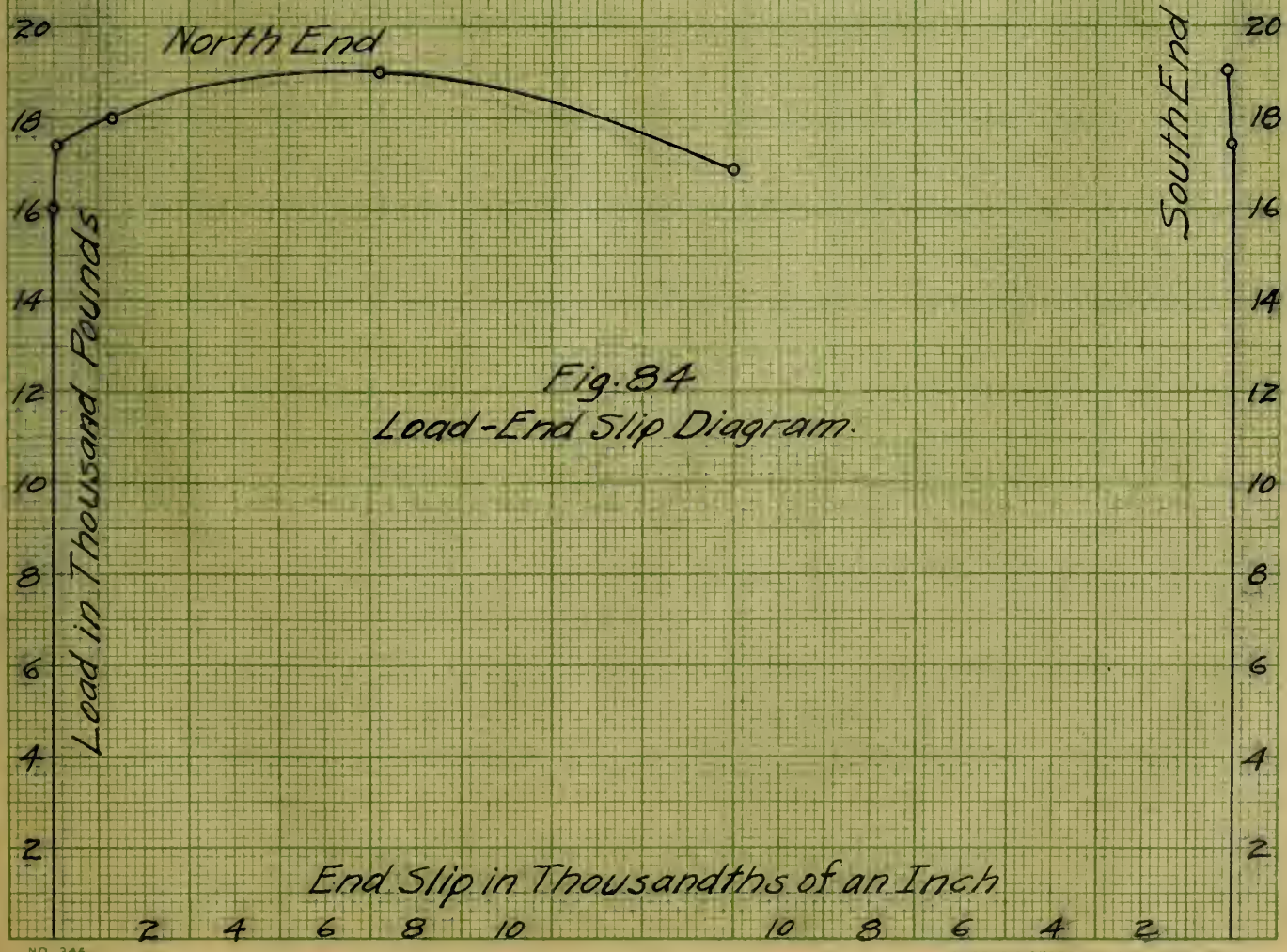
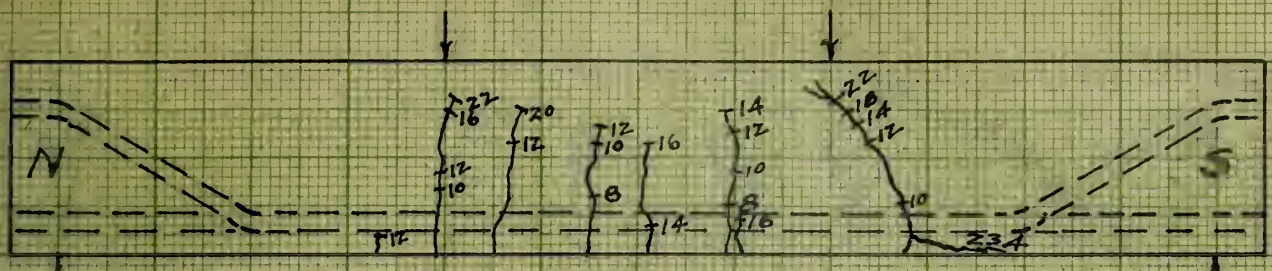


Fig. 84
Load-End Slip Diagram.

NO 346
EUGENE DIETZGEN CO. CHICAGO-NEW YORK



Beam 1088.1
Two 3/4 in. Plain Round

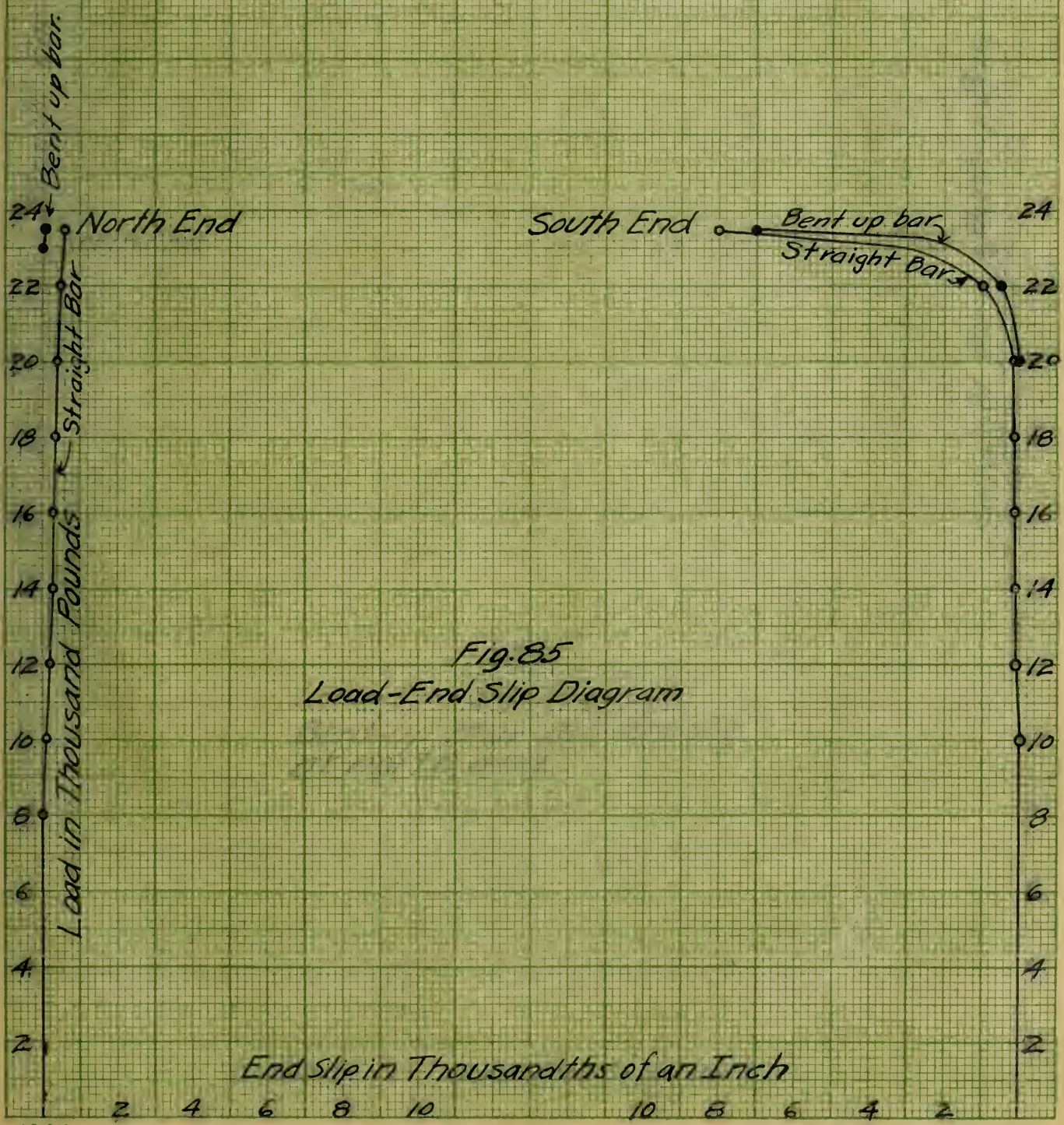
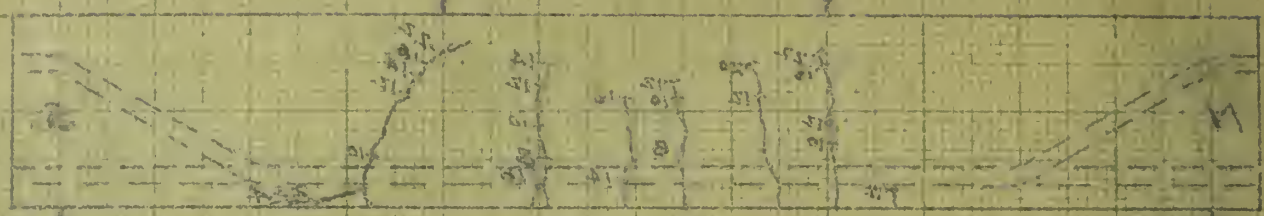
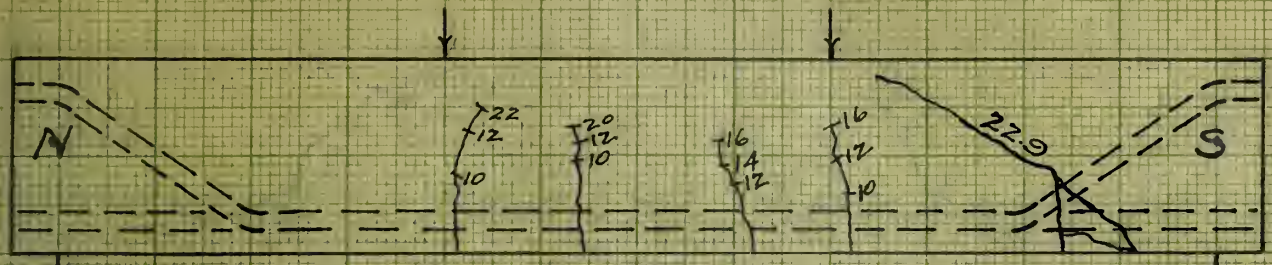


Fig. 85
Load-End Slip Diagram





Beam 1088.2
Two 3/4 in. Plain Round

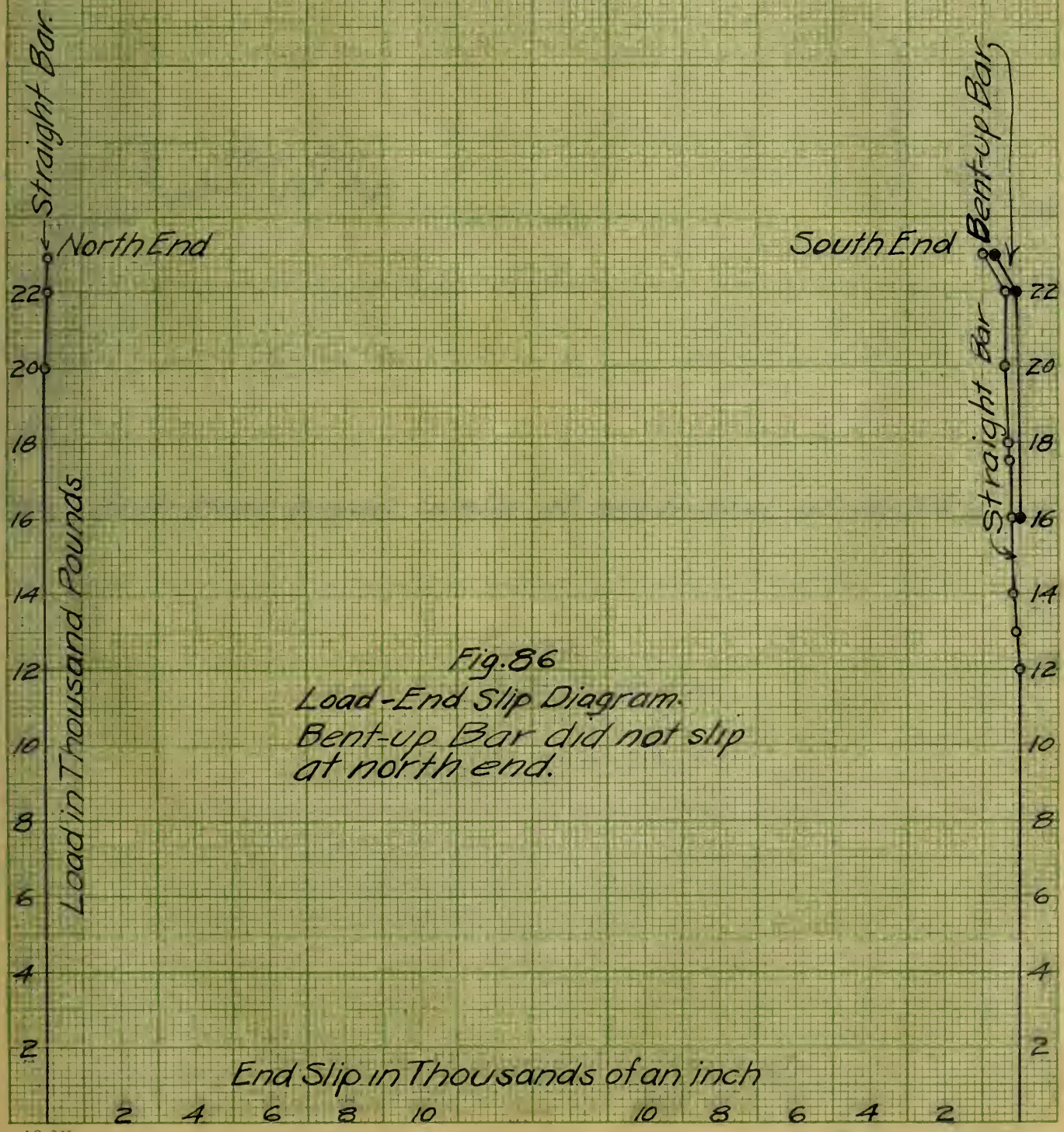


Fig. 86
Load-End Slip Diagram.
Bent-up Bar did not slip at north end.

NO 346
EUGENE L. ETZGEN CO. CHICAGO NEW YORK

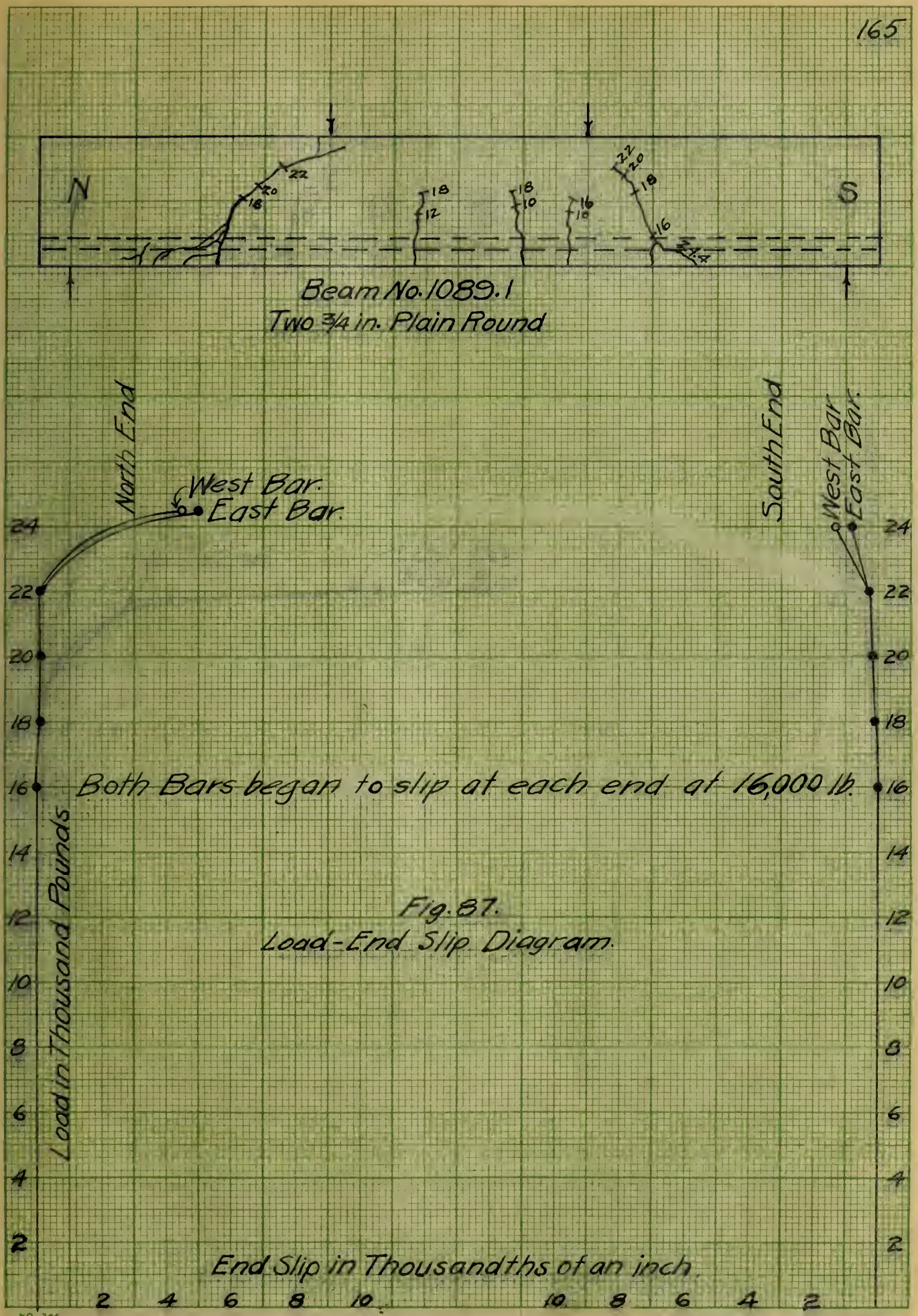
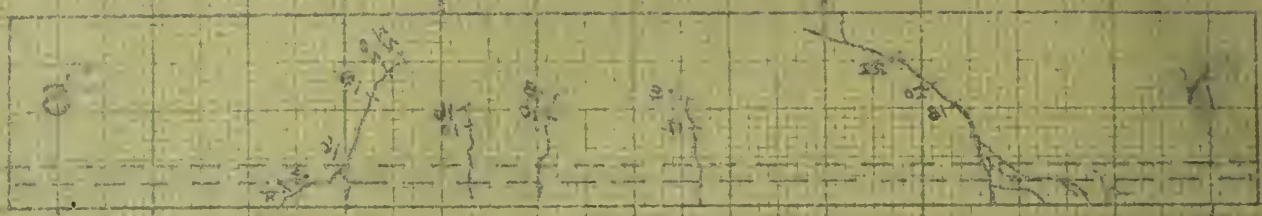


Fig. 87.
Load-End Slip Diagram.

NO 346
EUGENE O ETZGEN CO CHICAGO NEW YORK



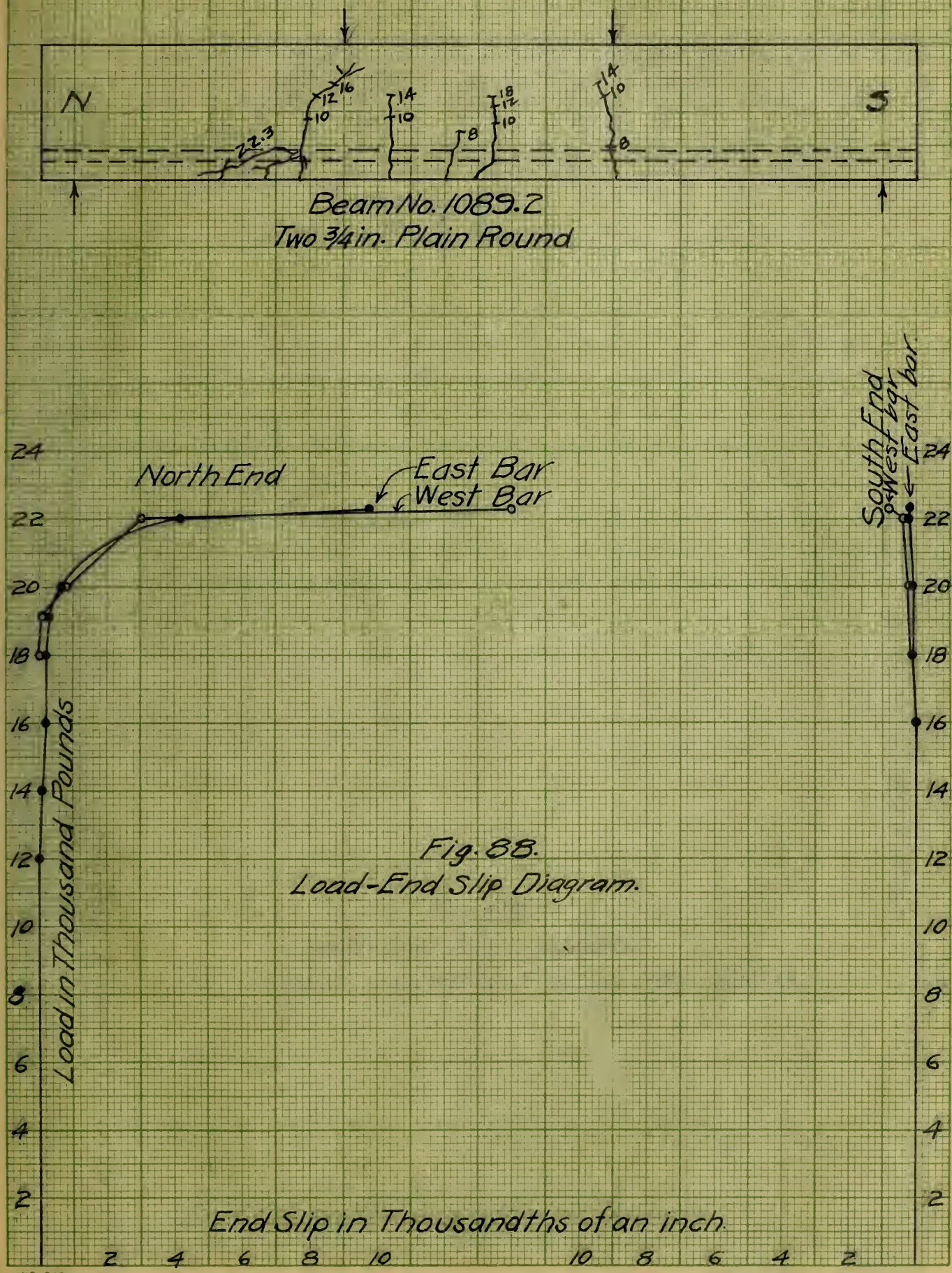
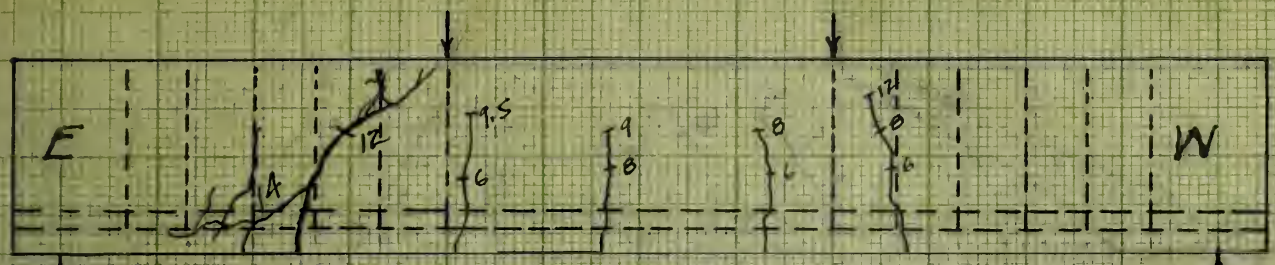


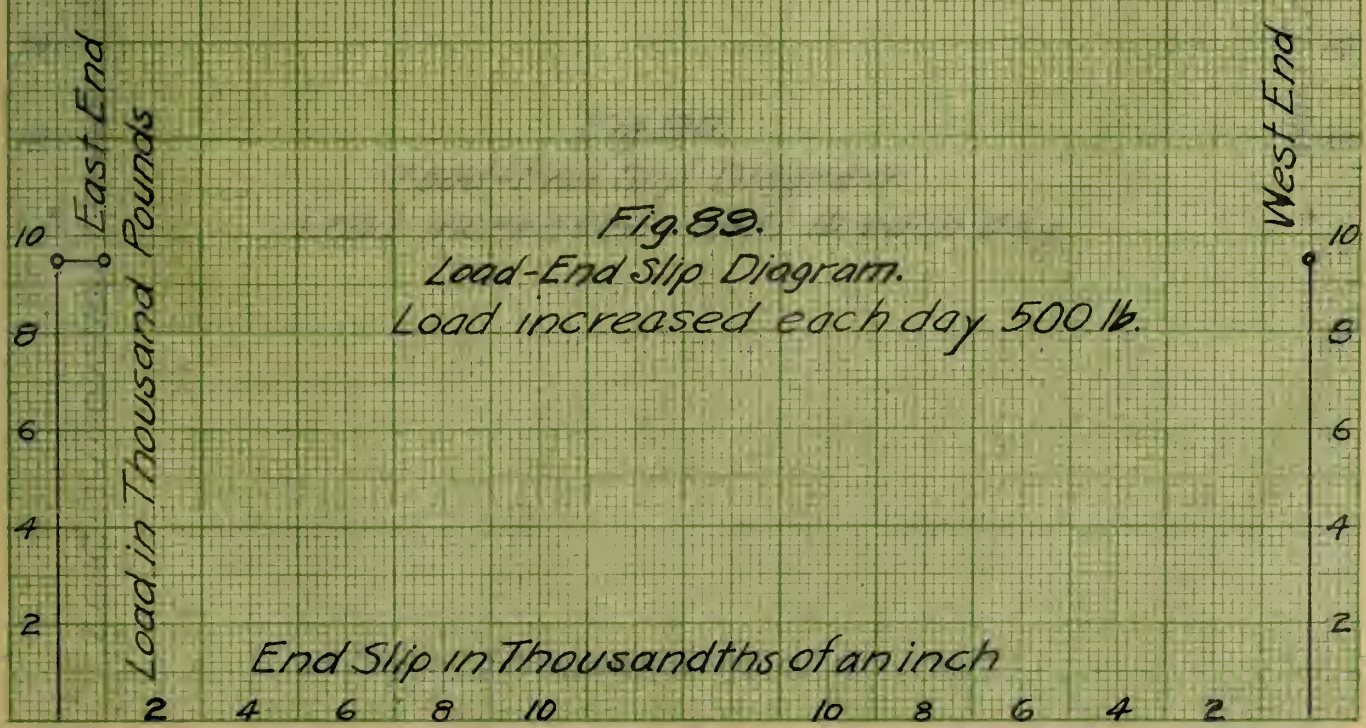
Fig. 88.
Load-End Slip Diagram.

NO 346
EUGENE DIETZGEN CO CHICAGO-NEW YORK

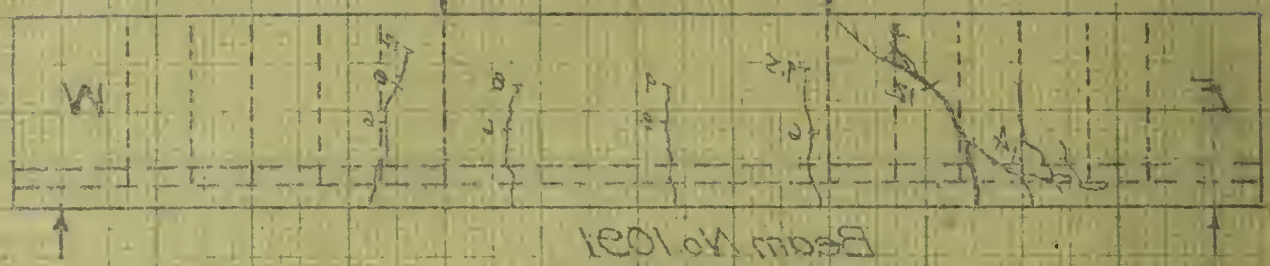


Beam No. 1091
One 1 in. Plain Round

Fig. 89.
Load-End Slip Diagram.
Load increased each day 500 lb.

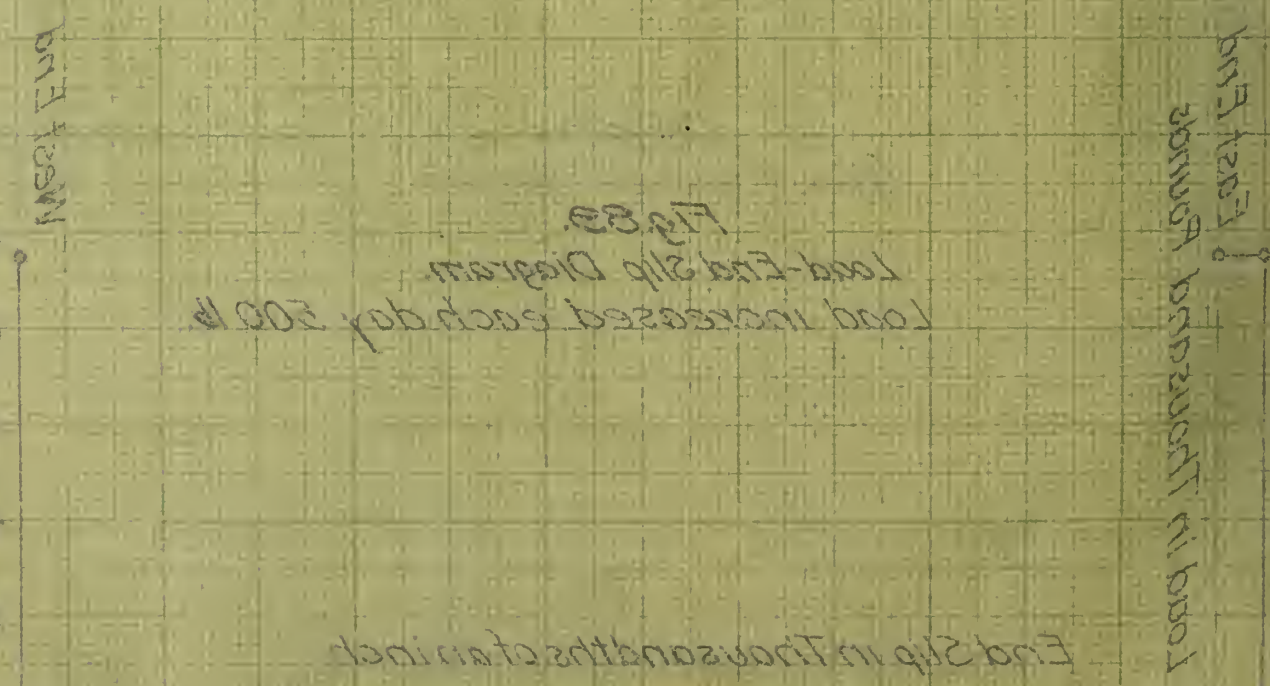


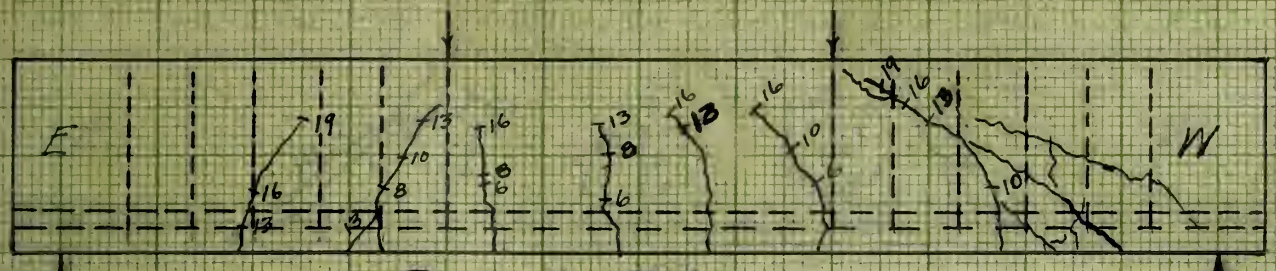
NO 346
EUGENE DIETZGEN CO. CHICAGO NEW YORK



Beam No 1091
One in Plain Round

Fig 39
Load-End Slip Diagram
Load increased each day 500 lb





Beam No. 1092
One $1\frac{1}{8}$ in. Corrugated Round

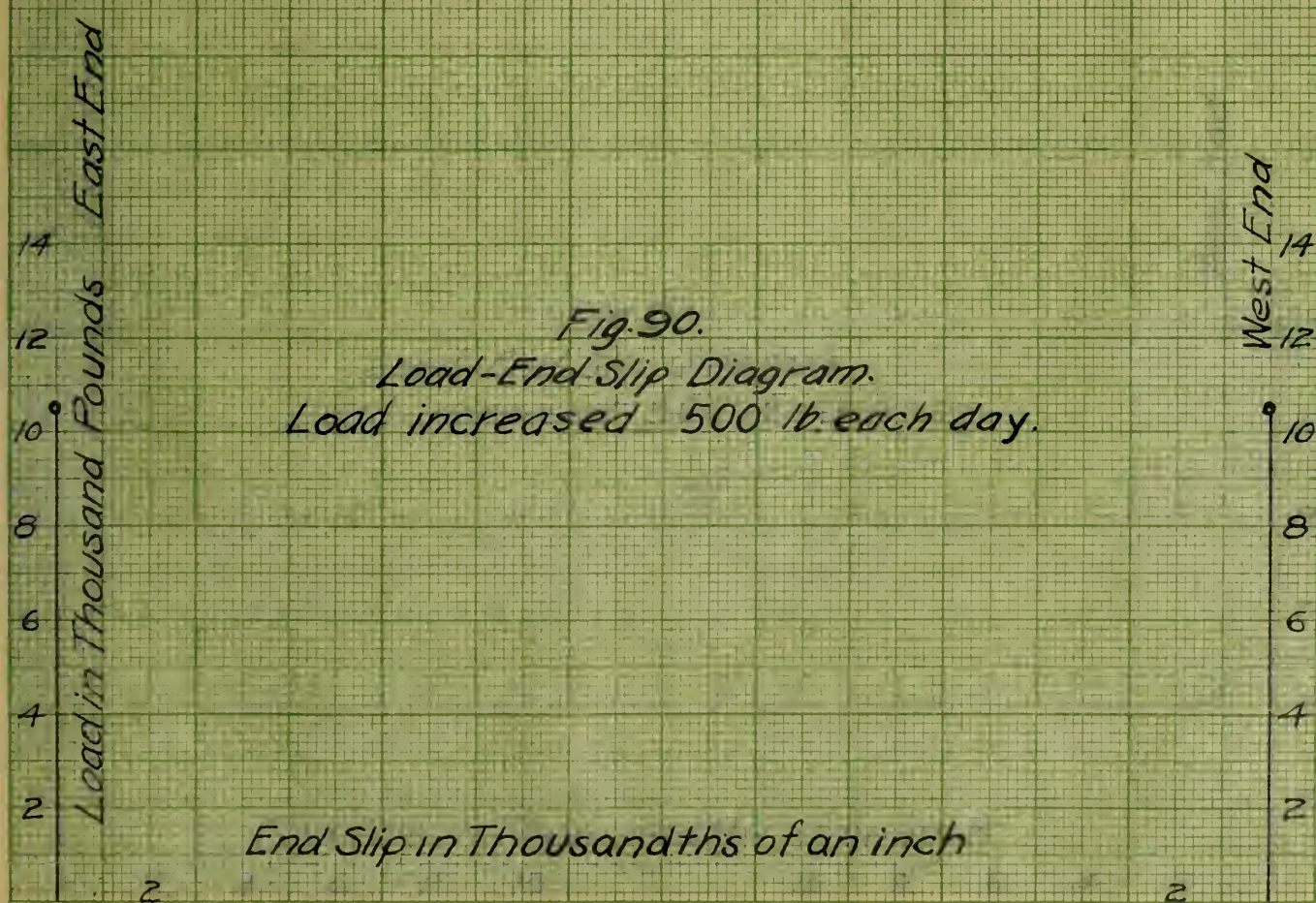
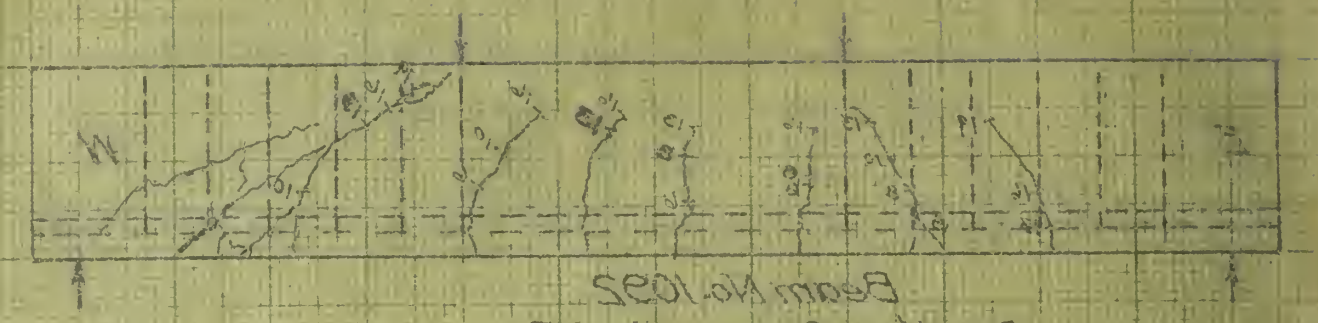
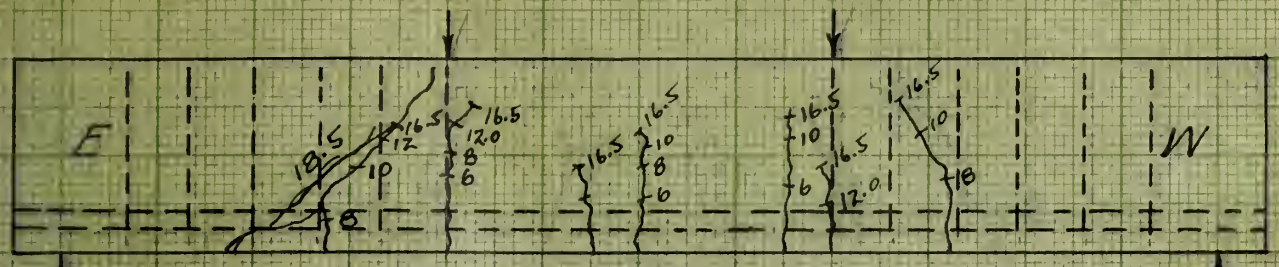


Fig. 90.
Load-End Slip Diagram.
Load increased 500 lb. each day.

NO 346
GENE ETZGEN C AGO NEW ORK





Beam No. 1093
One 1 in. Twisted Square

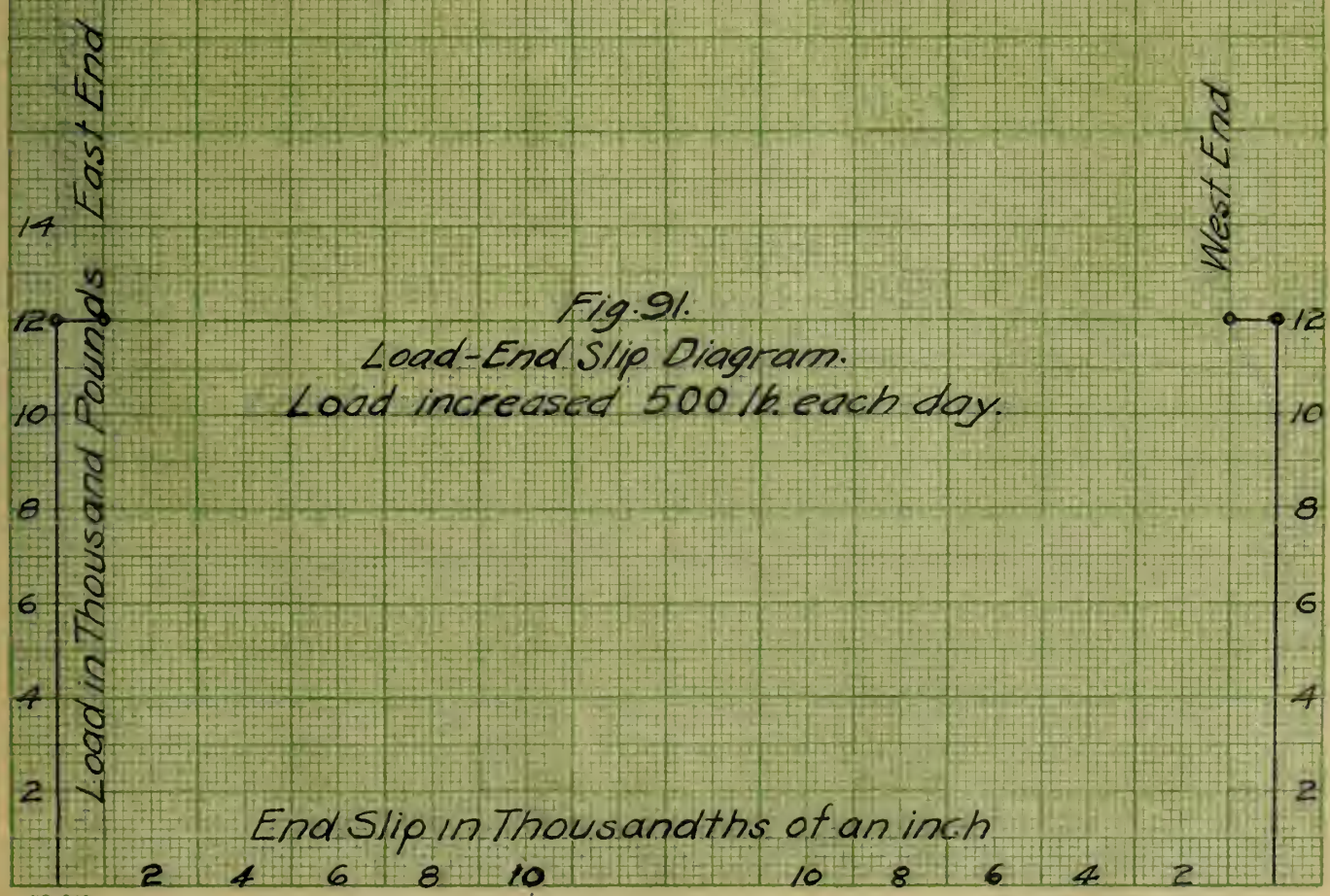
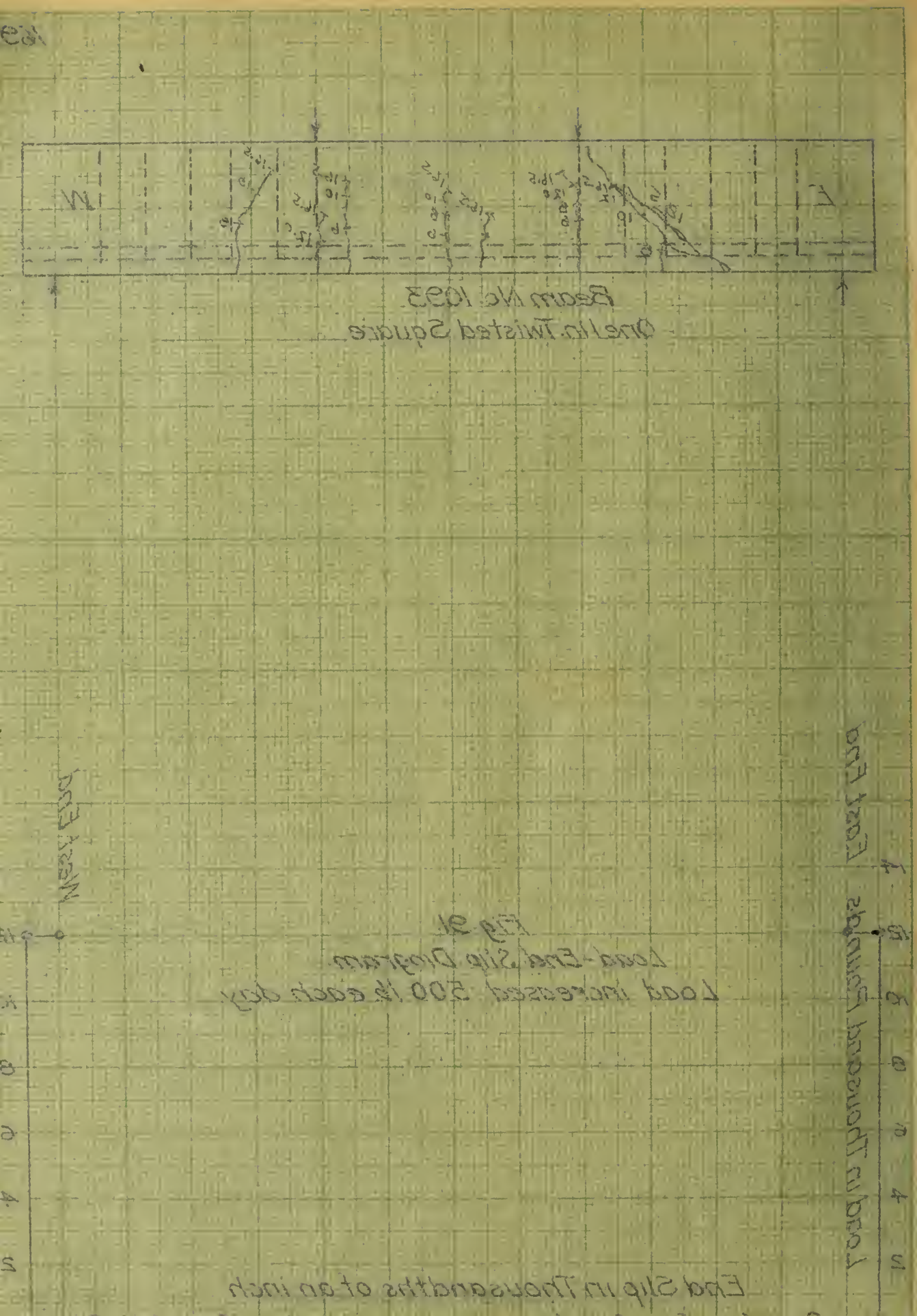
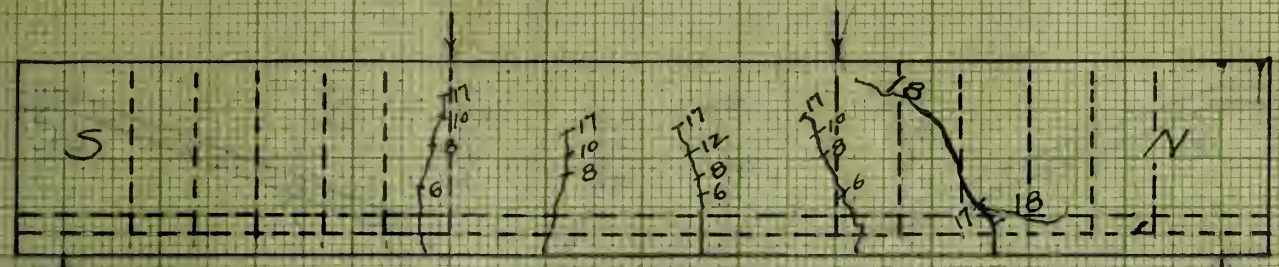


Fig. 91.
Load-End Slip Diagram.
Load increased 500 lb. each day.

NO 346
EUGENE DIETZGEN CO. CHICAGO NEW YORK





Beam No. 1094
One 1 in. Plain Round

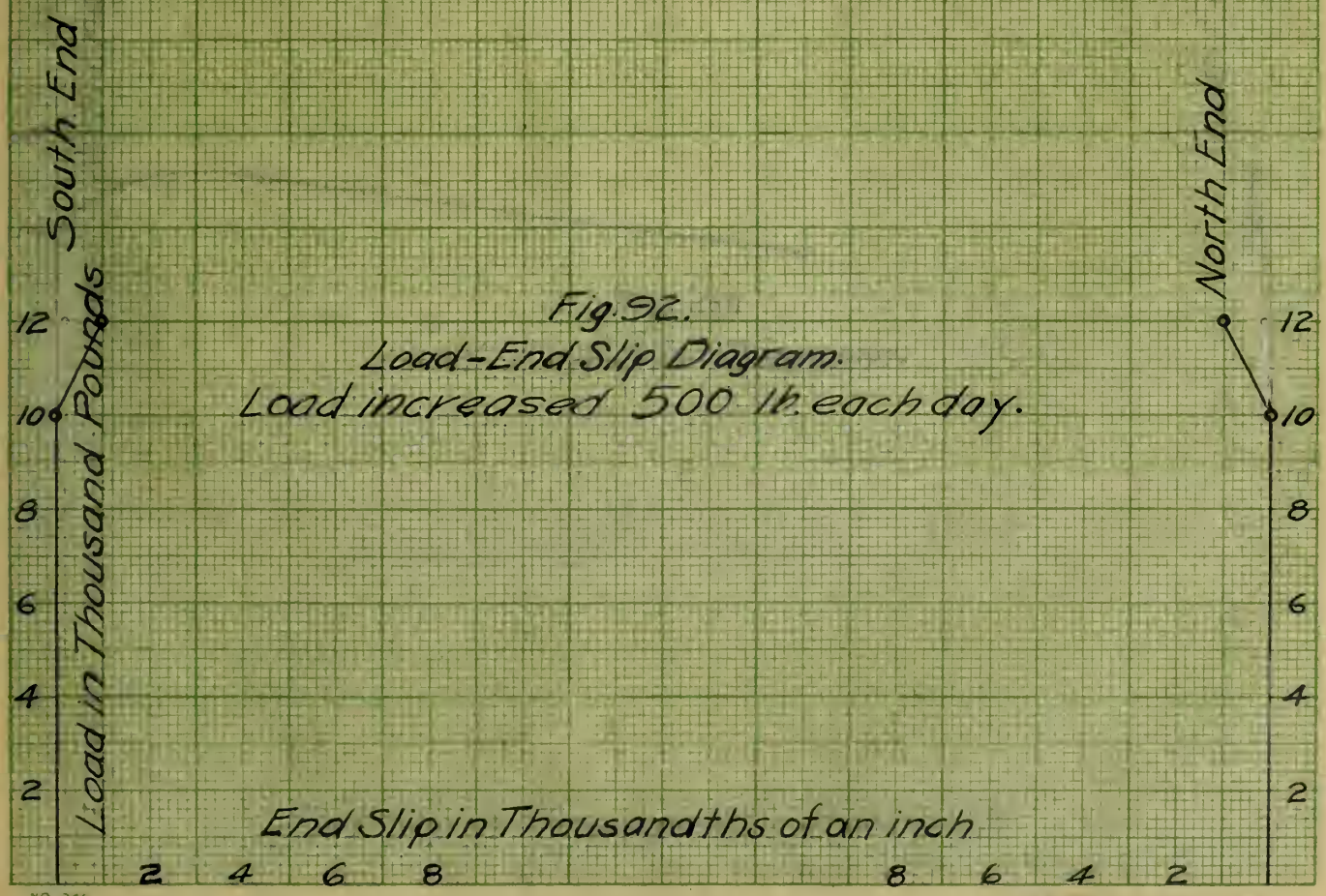
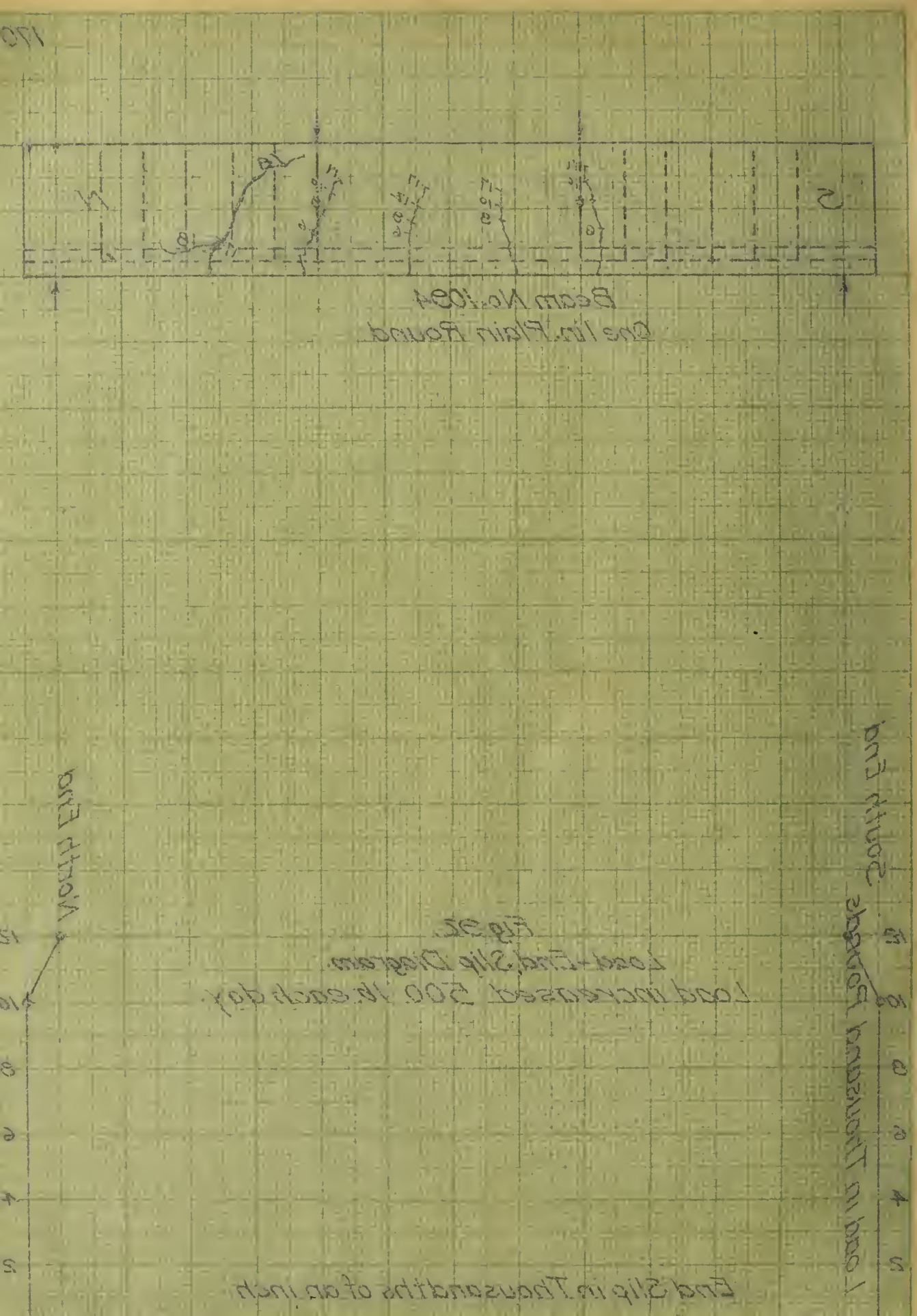
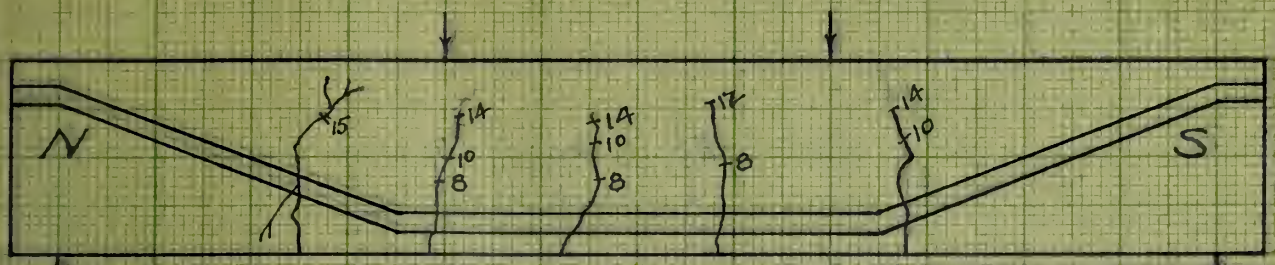


Fig. 92.
Load-End Slip Diagram.
Load increased 500 lb. each day.

NO 346
EUGENE E. WEM CO CHICAGO NEW YORK





Beam No. 1095.1
One 1 in. Plain Round

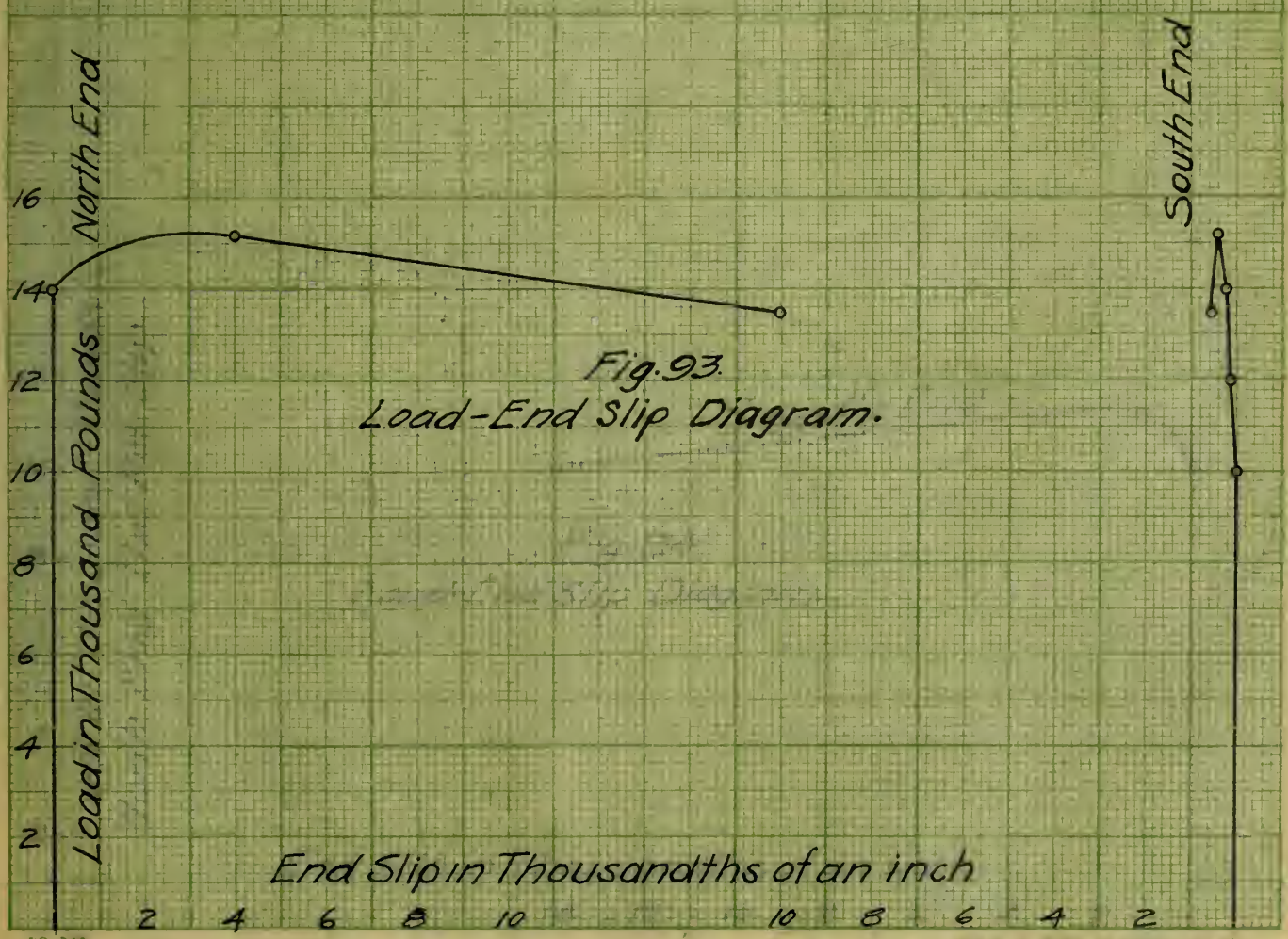
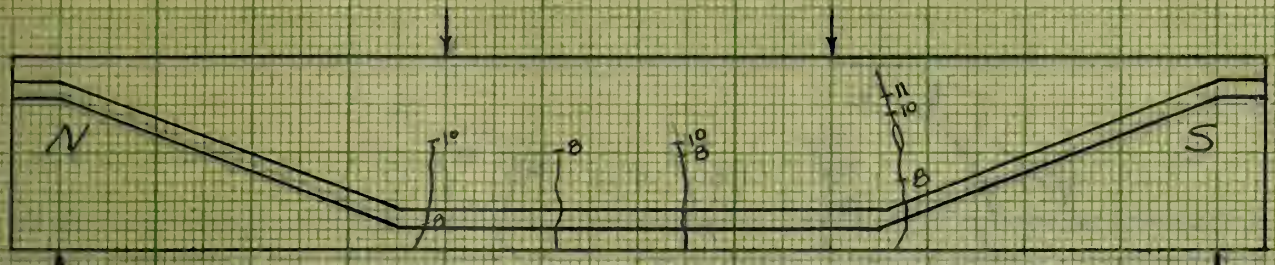


Fig. 93.
Load-End Slip Diagram.

Beam No. 1035.1
One Inch Plain Round



Beam No. 1095.2
One 1in. Plain Round

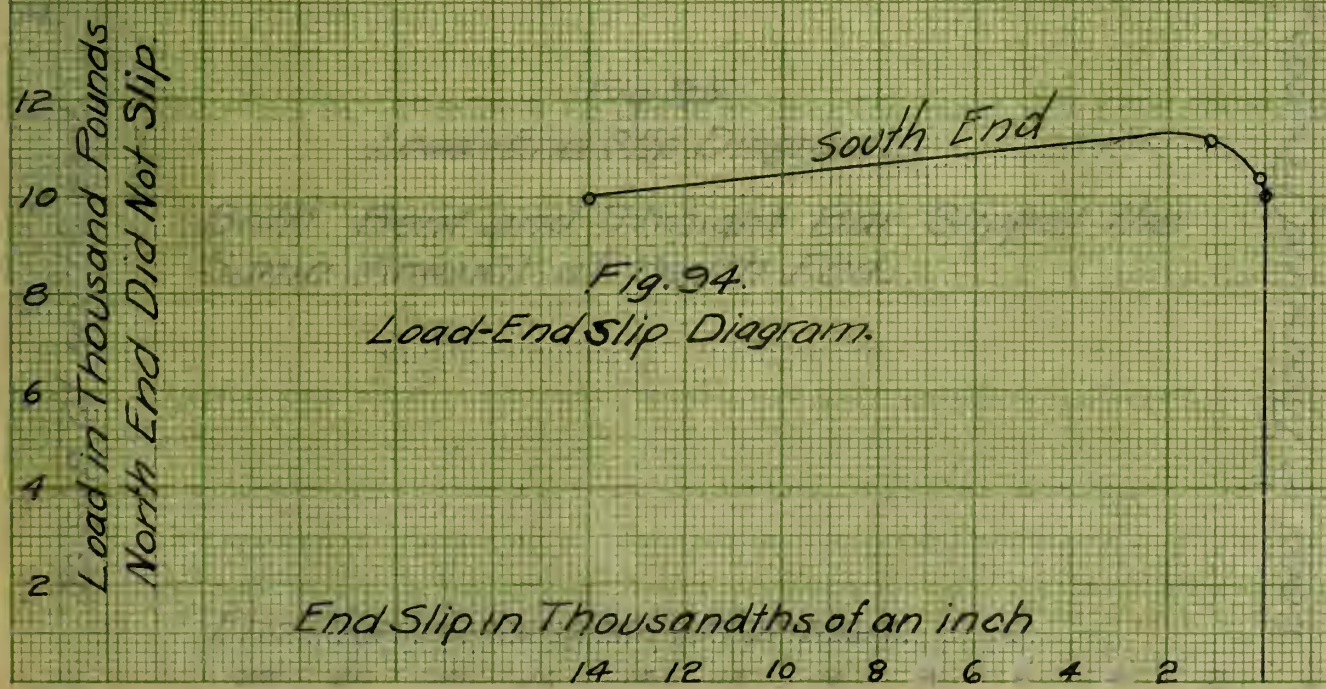
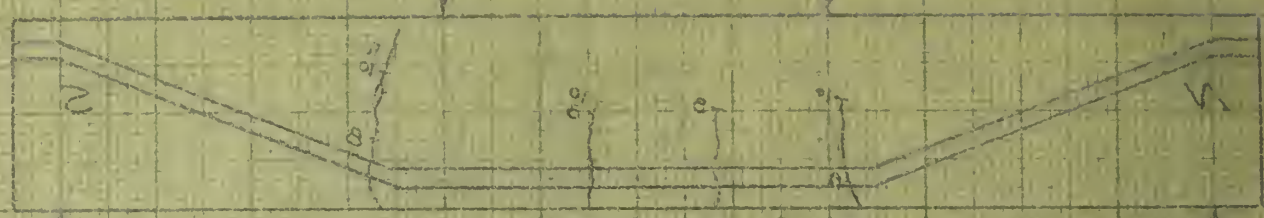


Fig. 94.
Load-End Slip Diagram.



Beam No. 1095.2
One Un. Plain Round

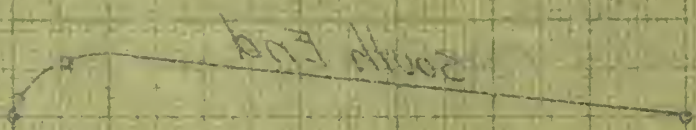
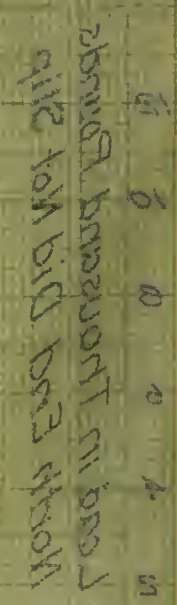
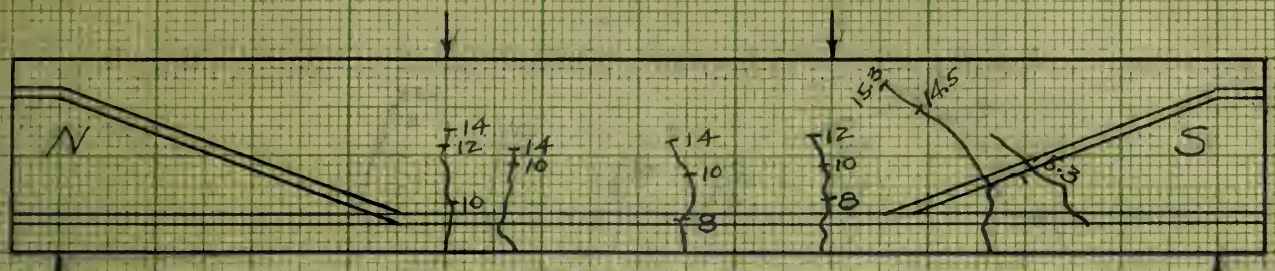


Fig. 34.
Load-End Slip Diagram



End Slip in Thousandths of an inch



Beam 1096.1
Two 3/4 in. Plain Round

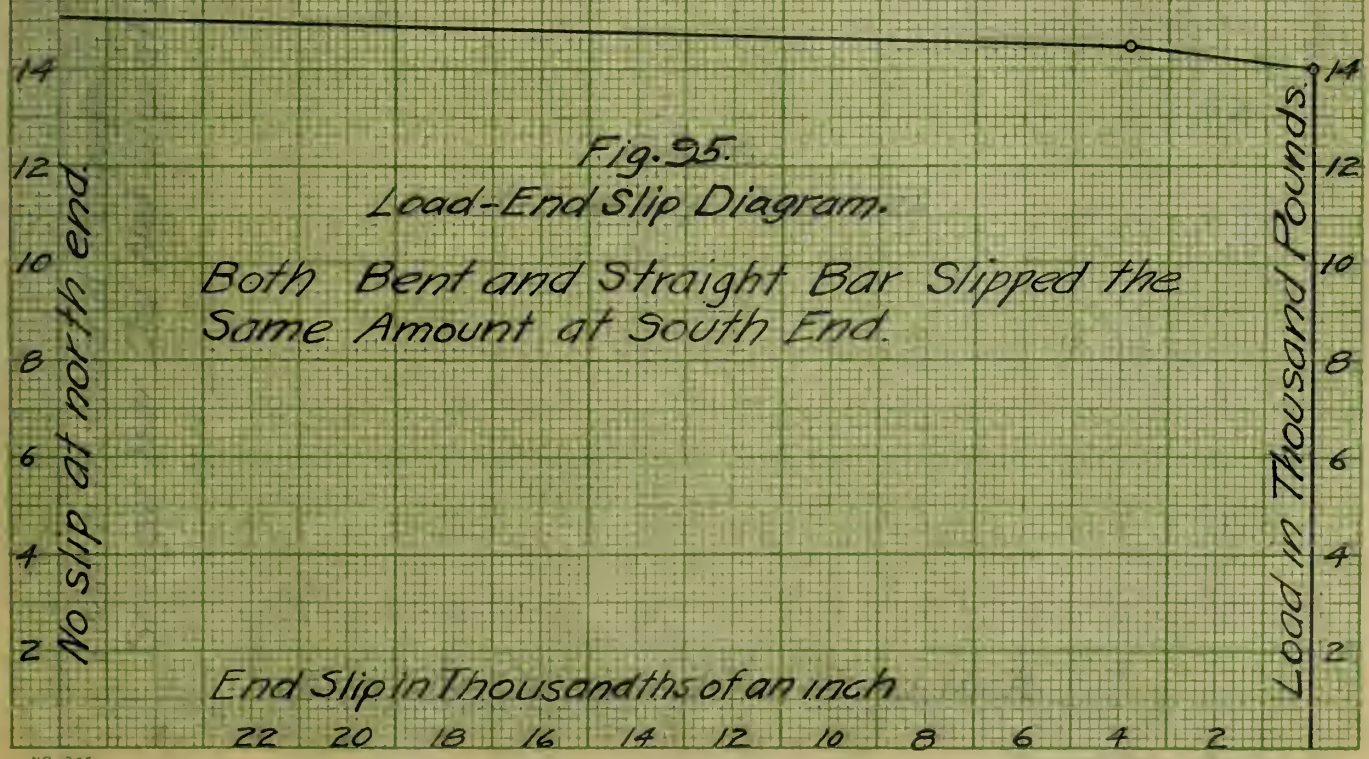


Fig. 95.
Load-End Slip Diagram.

Both Bent and Straight Bar Slipped the Same Amount at South End.

NO 346
EUGENE ETTGEN CO. CHICAGO NEW YORK

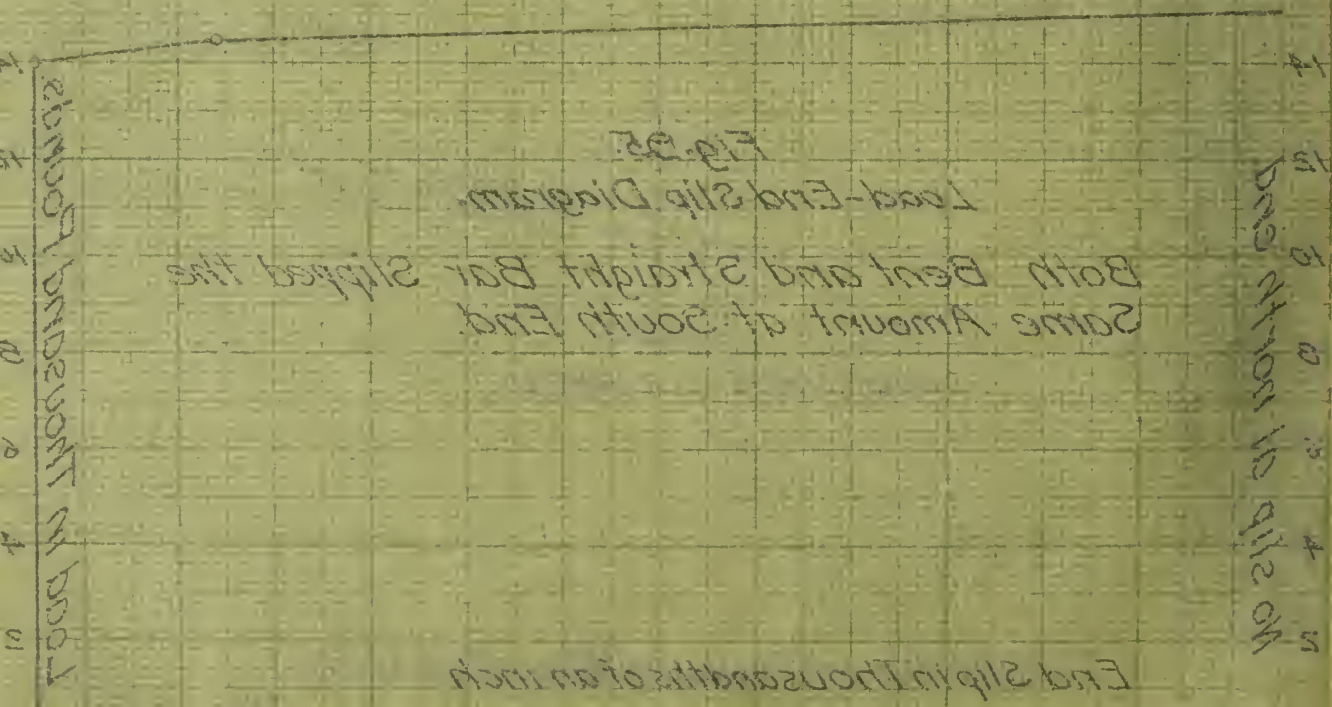
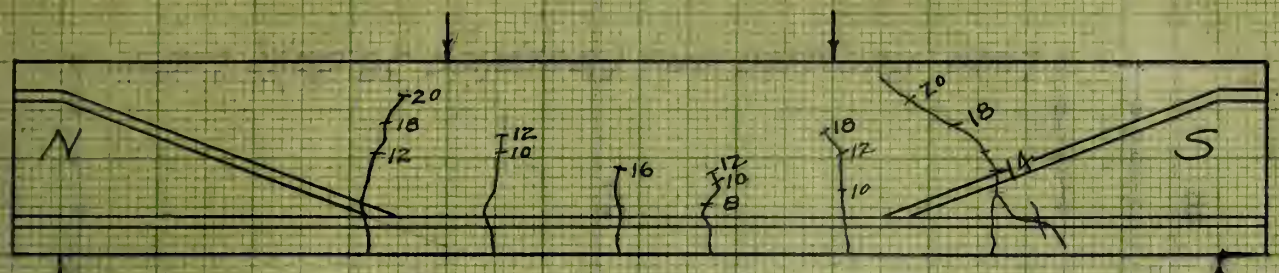


Fig. 35.

Load-End Slip Diagram.

Both Bent and Straight Bar Slipped the Same Amount at South End.

End Slip in Thousandths of an Inch



Beam No. 1096.2
Two 3/4 in. Plain Round

Fig. 96.
Load-End Slip Diagram.

Fig. 36.
Load-End Slip Diagram.

Beam No. 1096.2
Two 3/4 in. Plain Round

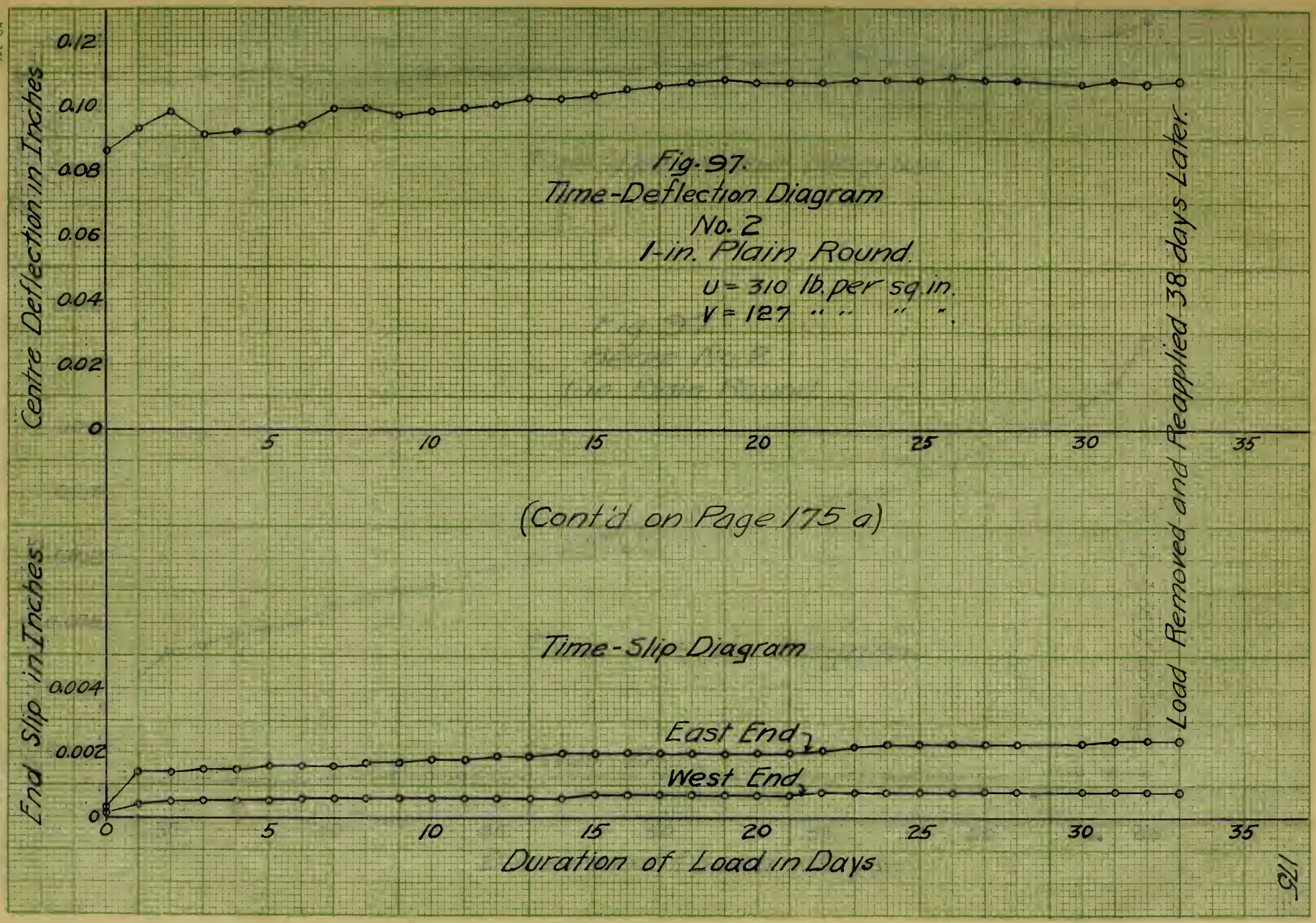
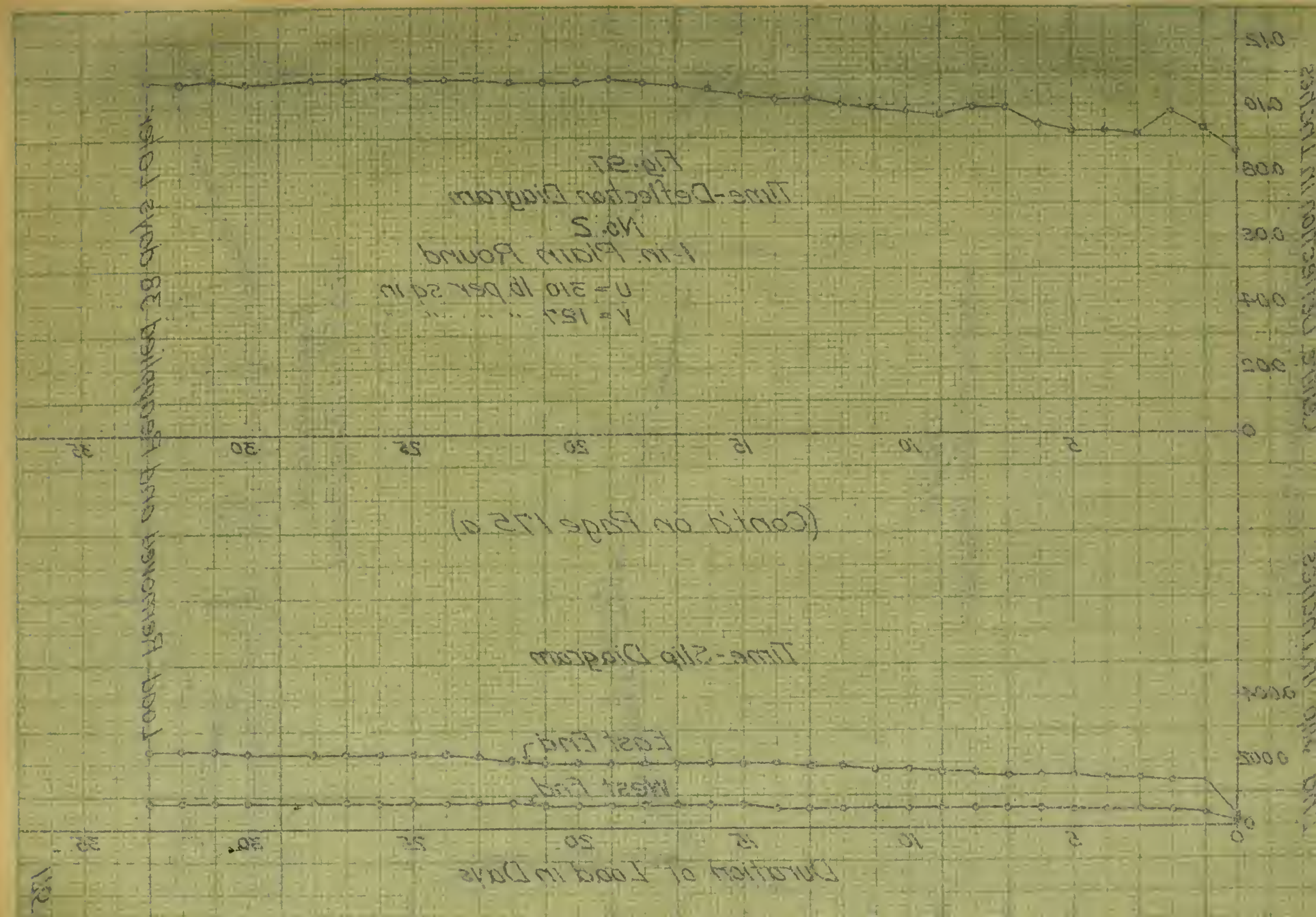
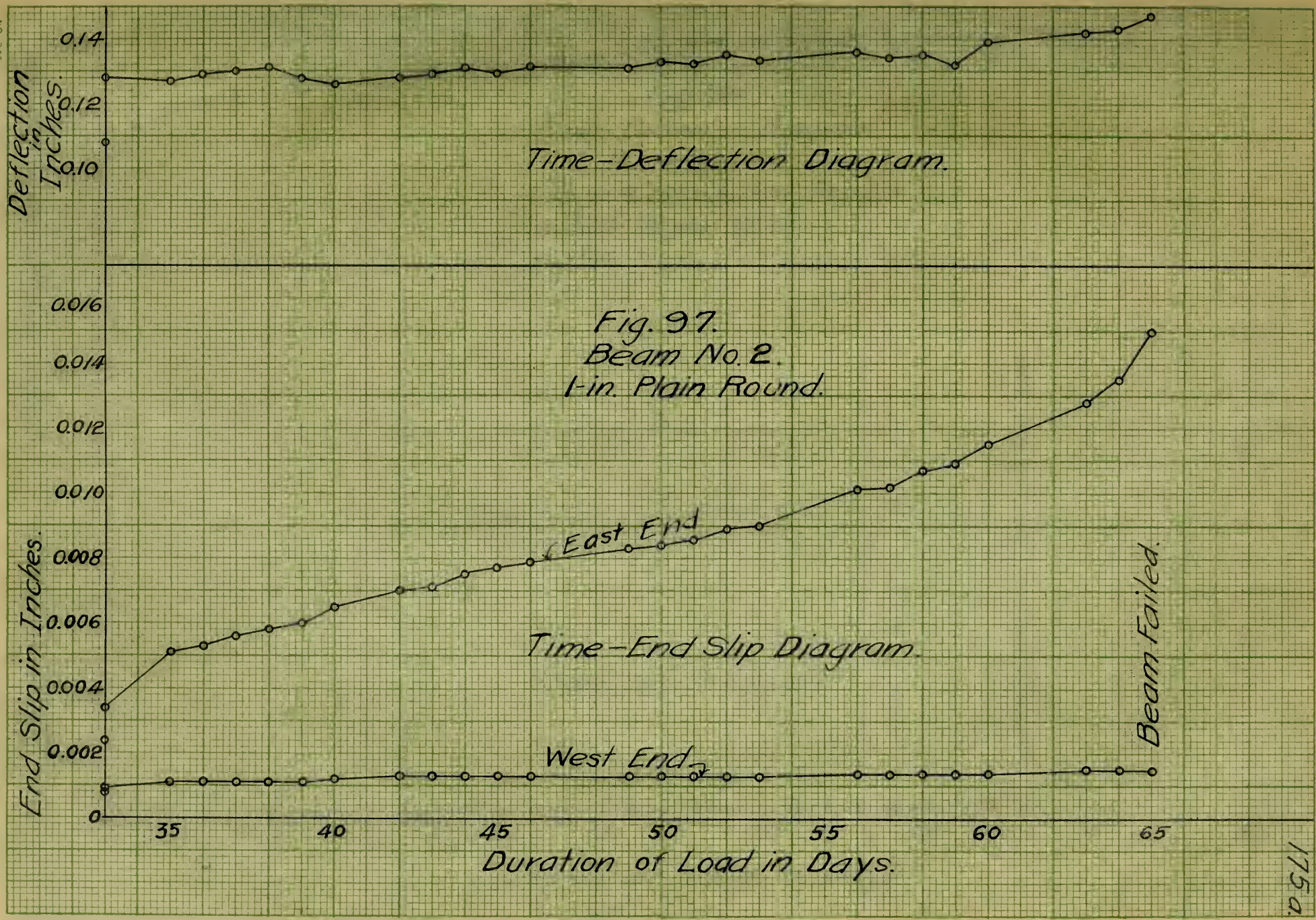


Fig. 97.
Time-Deflection Diagram
No. 2
1-in. Plain Round.
u = 310 lb. per sq. in.
v = 127 " " " ".

(Cont'd on Page 175 a)



(Cont'd on Page 175 a)


Deflection in Inches.
0.14
0.12
0.10
Time-Deflection Diagram.
Fig. 97.
Beam No. 2.
1-in. Plain Round.
0.016
0.014
0.012
0.010
0.008
0.006
0.004
0.002
0
End Slip in Inches.
East End
Time-End Slip Diagram.
West End
Beam Failed.
35
40
45
50
55
60
65
Duration of Load in Days.

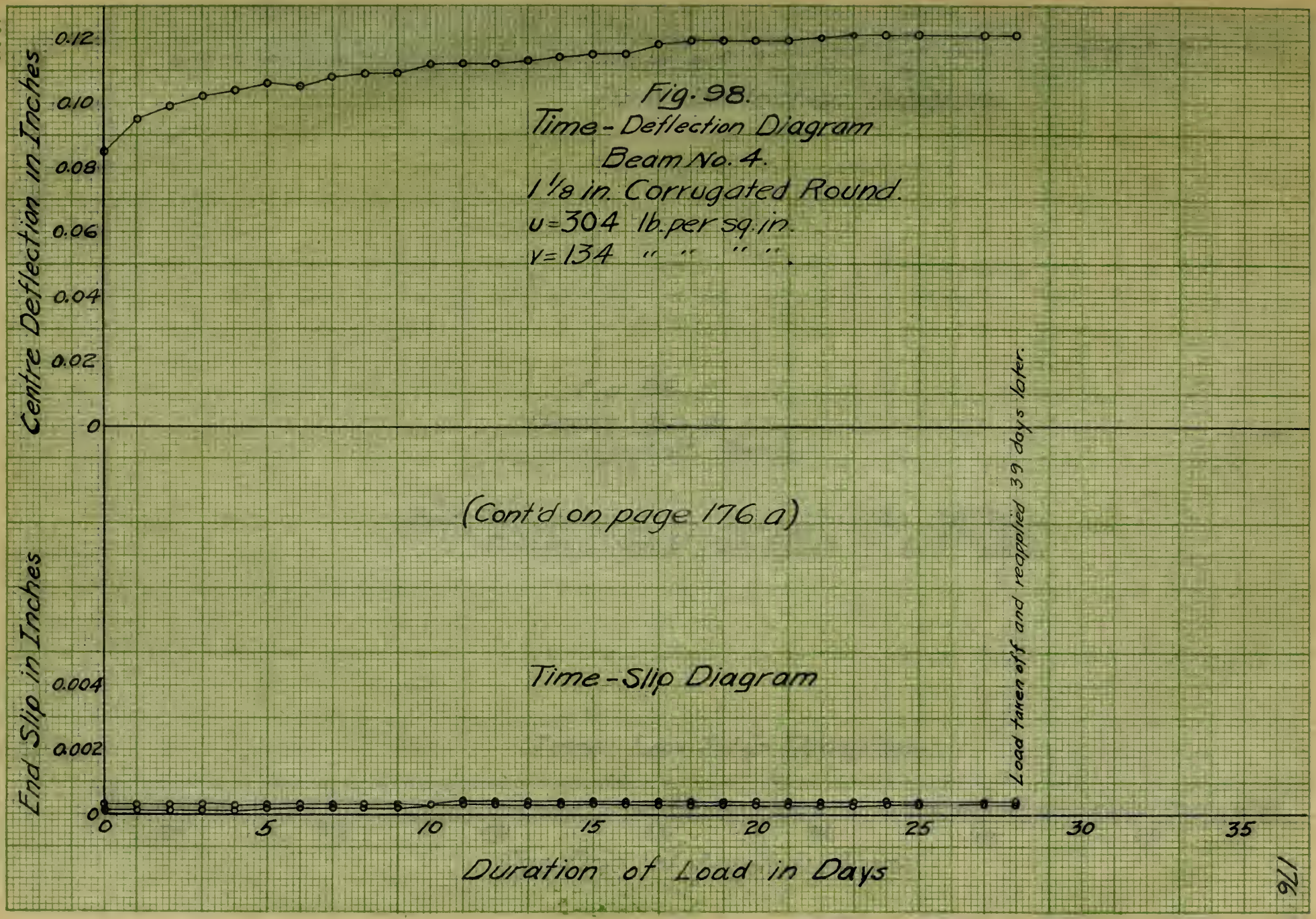
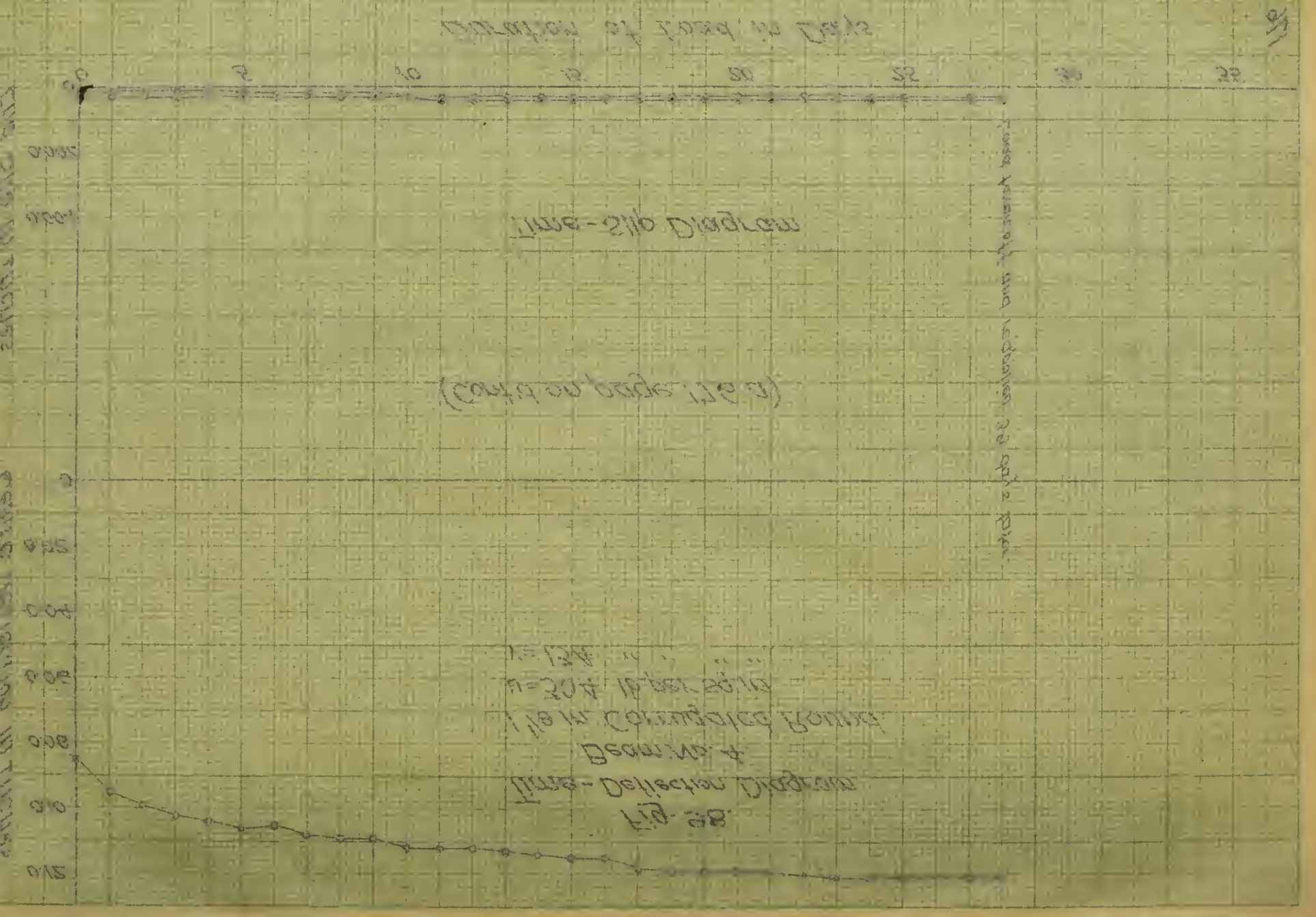

Centre Deflection in Inches
0.12
0.10
0.08
0.06
0.04
0.02
0
Time-Deflection Diagram
Beam No. 4.
1 1/8 in. Corrugated Round.
u=304 lb. per sq. in.
v=134 " " " "
(Cont'd on page 176 a)
End Slip in Inches
0.004
0.002
0
Time-Slip Diagram
Load taken off and reapplied 39 days later.
0
5
10
15
20
25
30
35
Duration of Load in Days

Fig. 98.



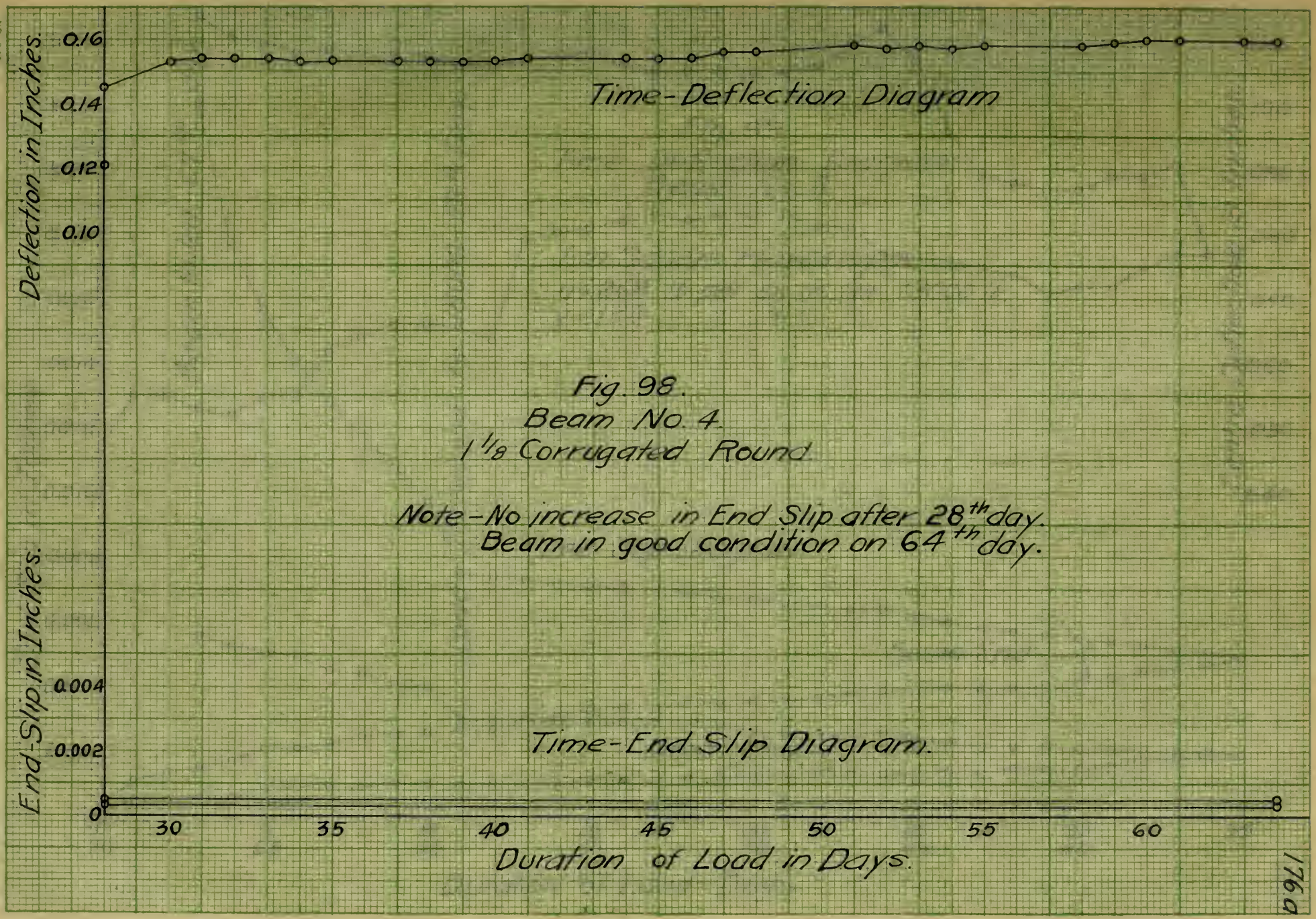
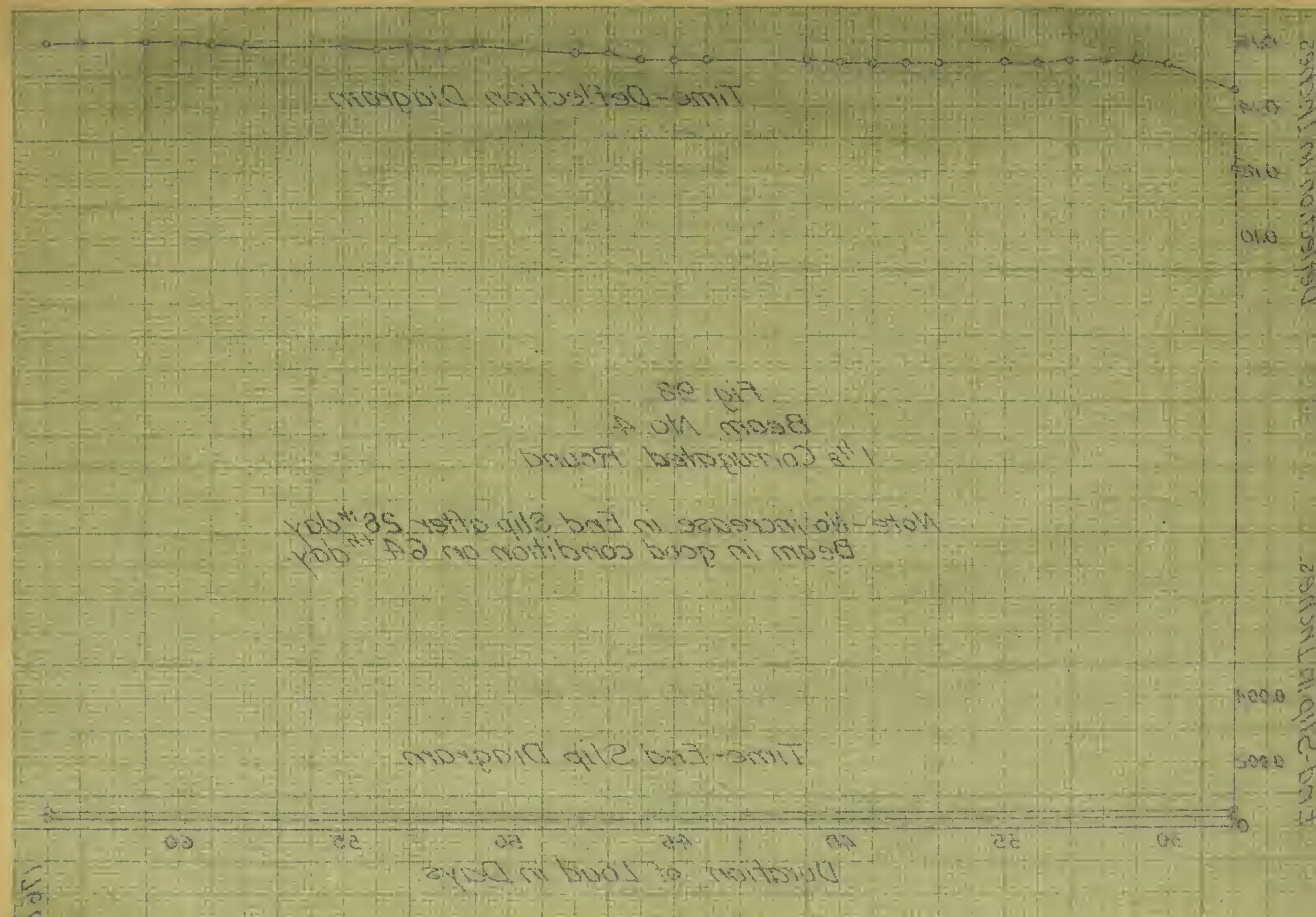


Fig. 98.
Beam No. 4.
1 1/8 Corrugated Round.

Note-No increase in End Slip after 28th day.
Beam in good condition on 64th day.


Time-Deflection Diagram
Fig. 98
Beam No. 4
1⅛ Corrugated Round
Note-No increase in End Slip after 28th day
Beam in good condition on 64th day
Time-End Slip Diagram
Duration of Load in Days
30
35
40
45
50
55
60
0.10
0.002
0.004

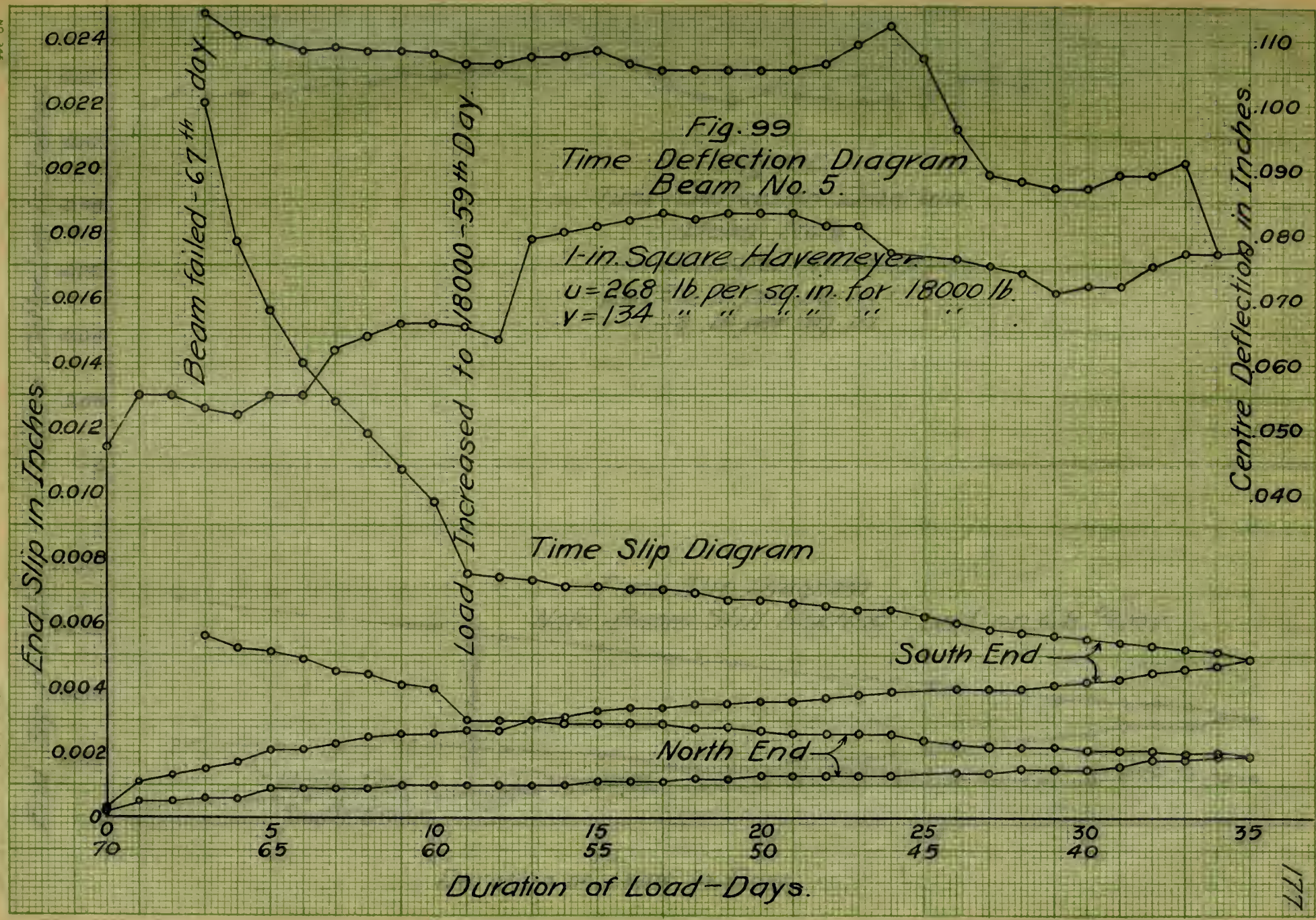
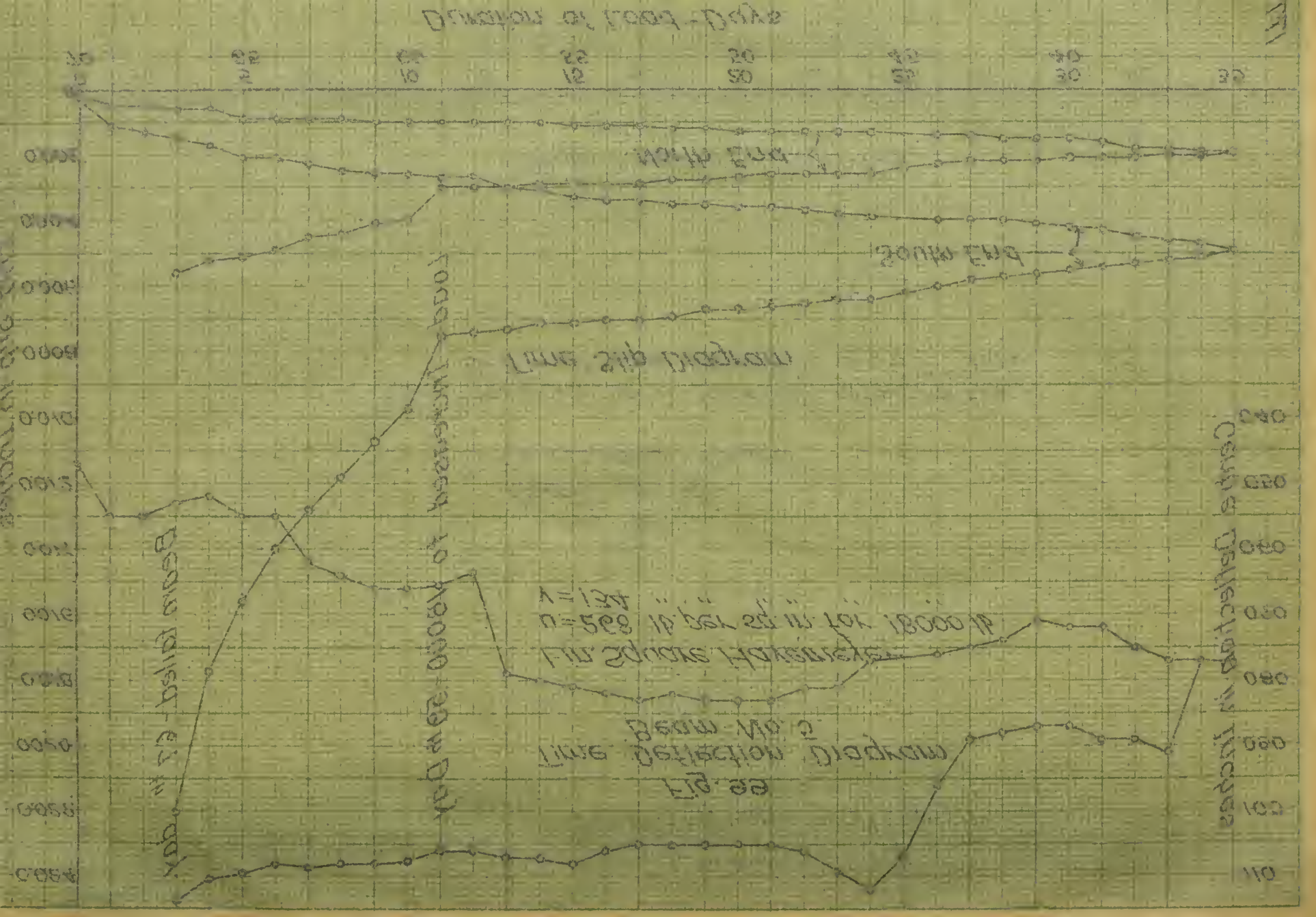
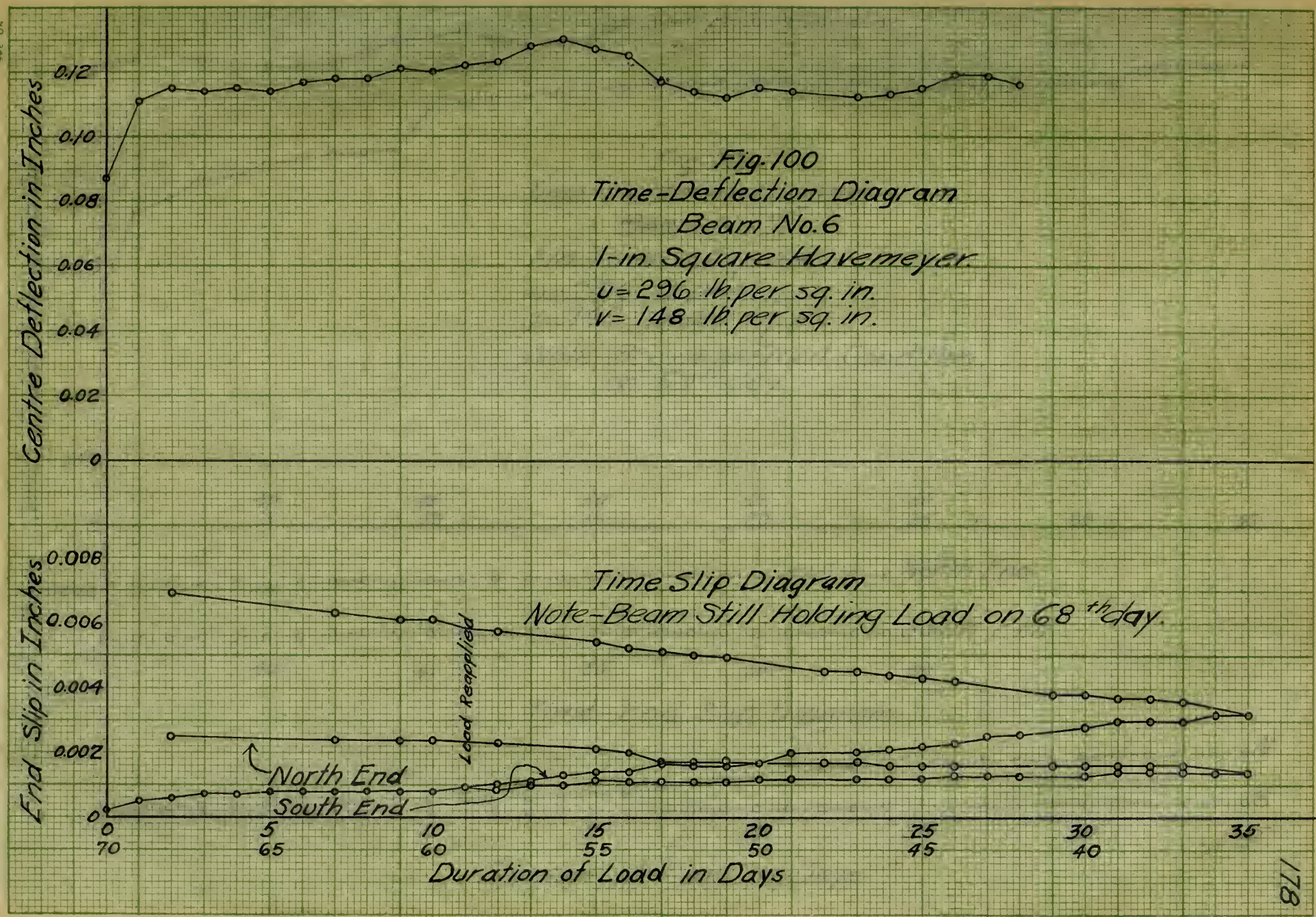


Fig. 99
Time Deflection Diagram
Beam No. 5.
1-in. Square Havemeyer
u=268 lb. per sq. in. for 18000 lb.
v=134 " " " " " "
Beam failed - 67th day.
Load Increased to 18000 - 59th Day.
Time Slip Diagram
South End
North End
End Slip in Inches
Centre Deflection in Inches
Duration of Load - Days.
0.024
0.022
0.020
0.018
0.016
0.014
0.012
0.010
0.008
0.006
0.004
0.002
0
.110
.100
.090
.080
.070
.060
.050
.040
0 5 10 15 20 25 30 35
70 65 60 55 50 45 40





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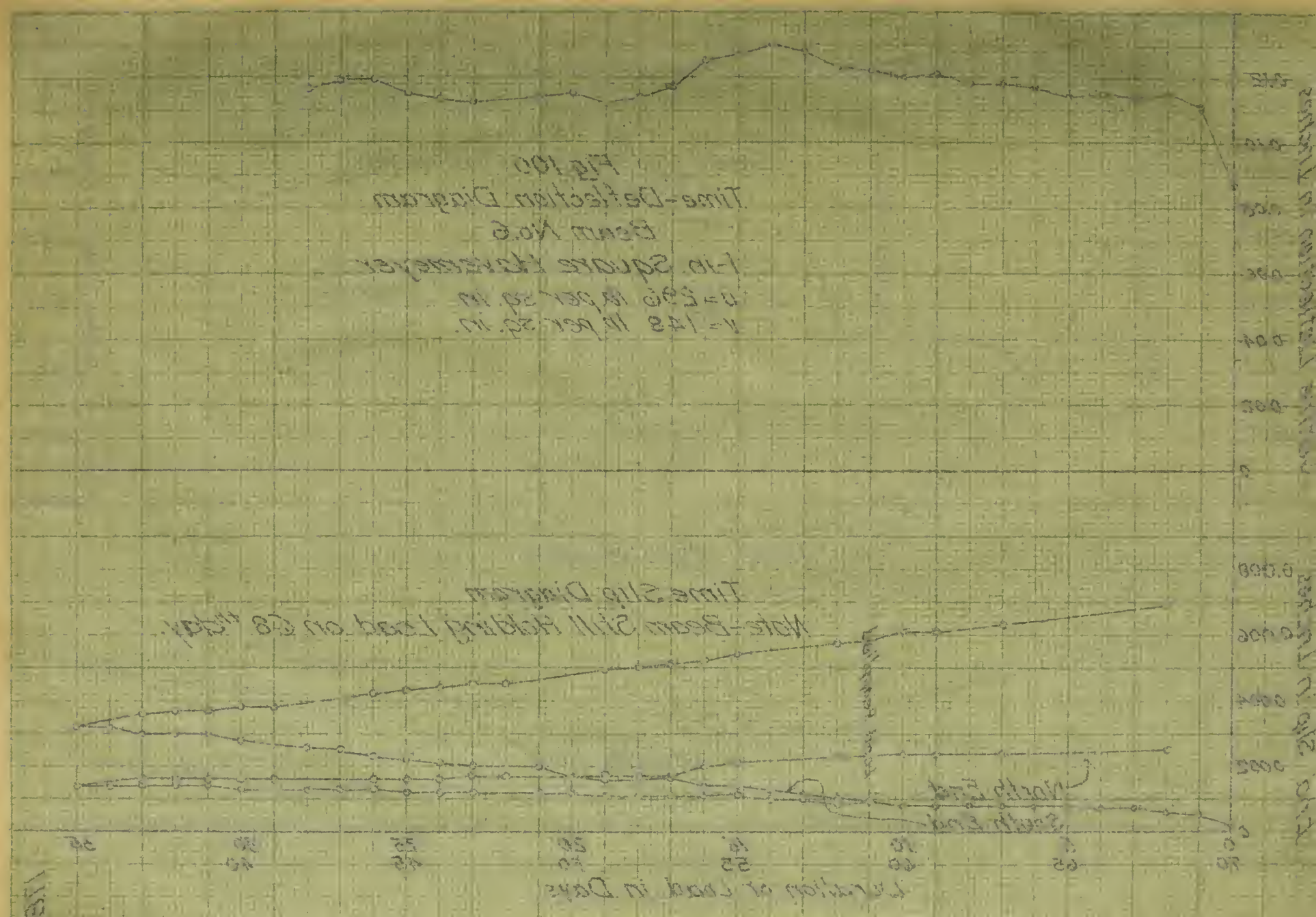


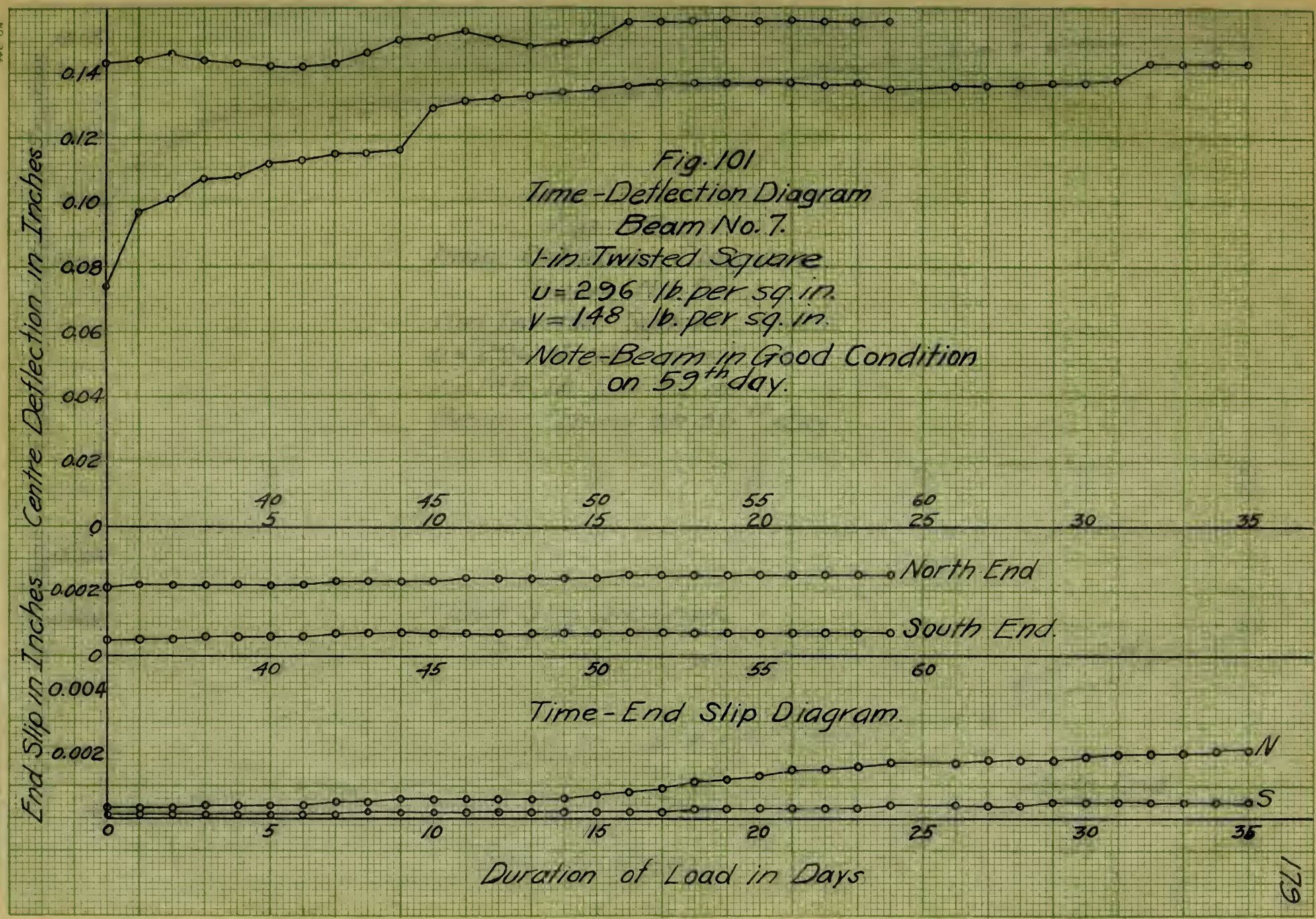
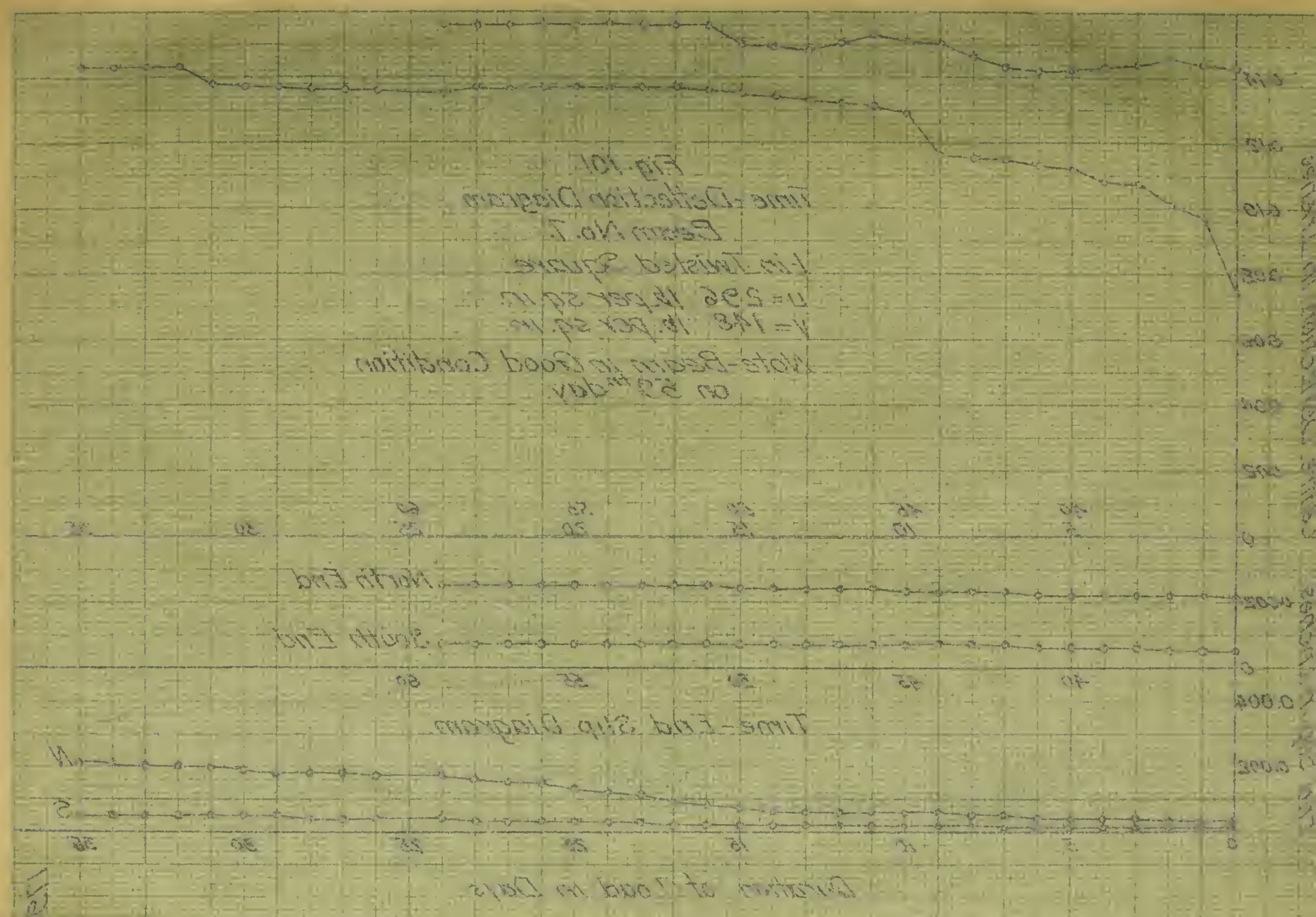
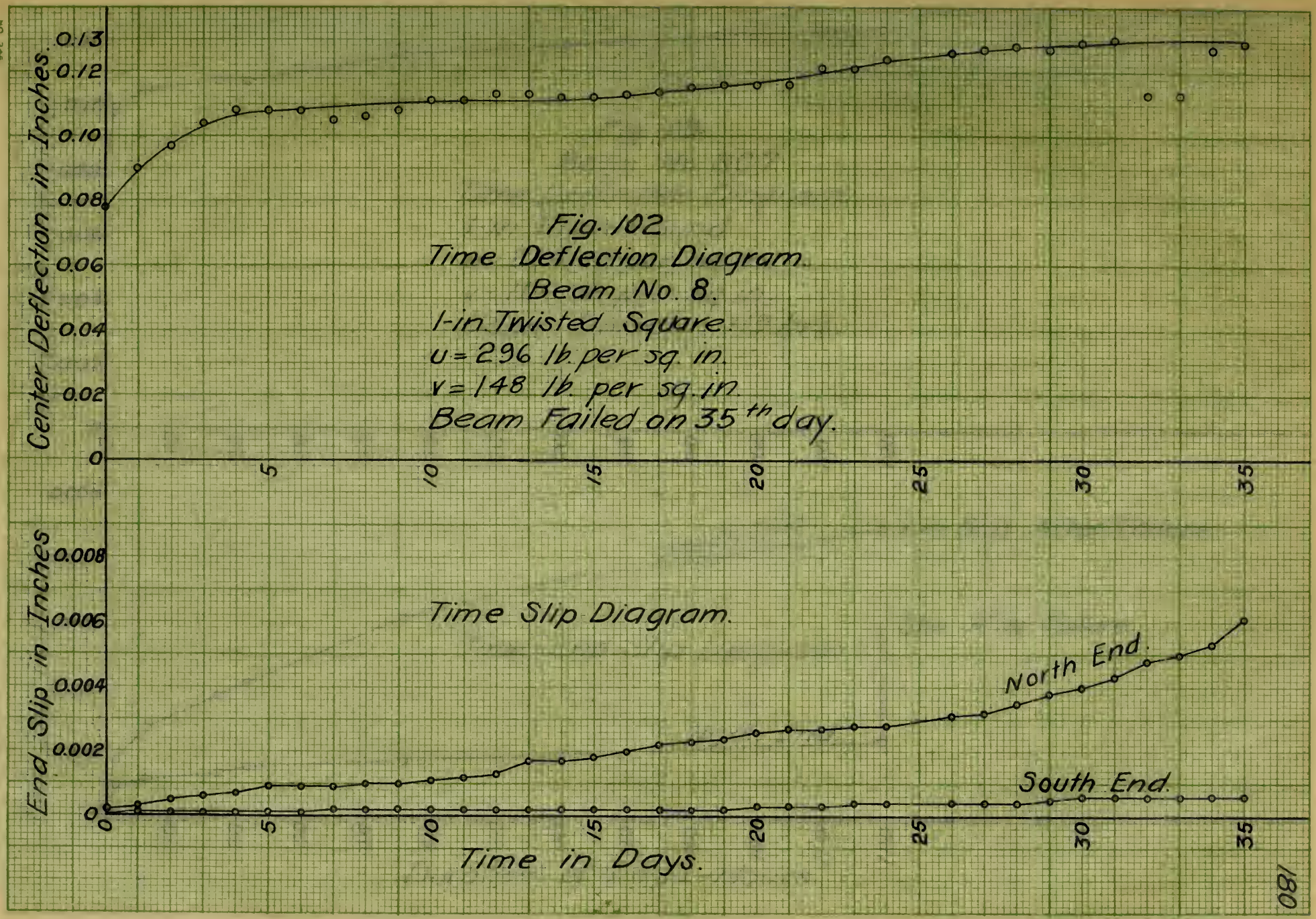


Fig. 101
Time-Deflection Diagram
Beam No. 7.
1-in. Twisted Square
u = 296 lb. per sq. in.
v = 148 lb. per sq. in.
Note-Beam in Good Condition on 59th day.




Center Deflection in Inches.
0.13
0.12
0.10
0.08
0.06
0.04
0.02
0
5
10
15
20
25
30
35
Fig. 102
Time Deflection Diagram.
Beam No. 8.
1-in. Twisted Square.
u = 296 lb. per sq. in.
v = 148 lb. per sq. in.
Beam Failed on 35th day.
End Slip in Inches
0.008
0.006
0.004
0.002
0
Time Slip Diagram.
North End.
South End.
Time in Days.

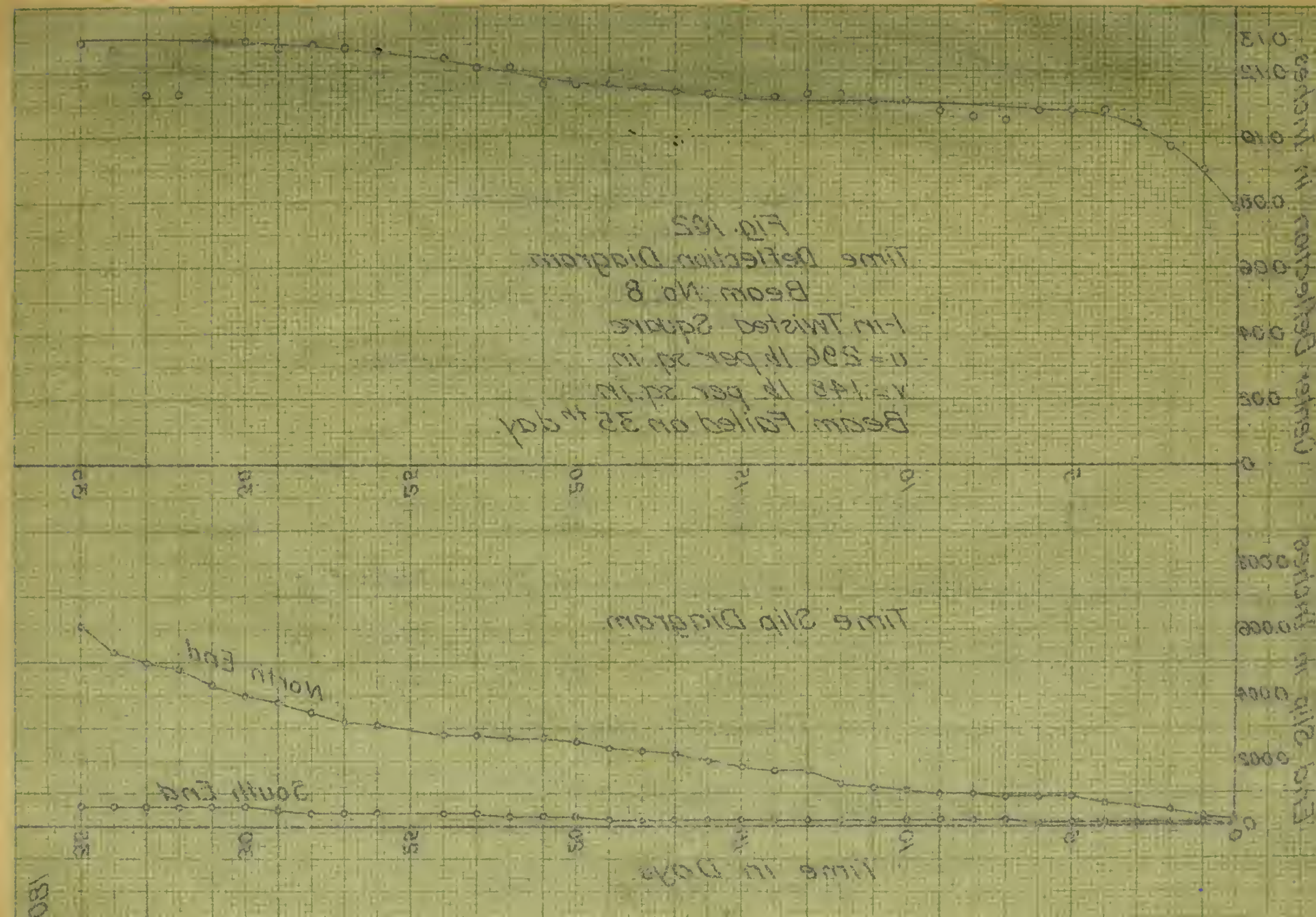


Fig. 162
Time Deflection Diagram
Beam No. 8
1-in Twisted Square
u = 296 lb per sq. in
v = 148 lb per sq. in
Beam Failed on 35th day
Time Slip Diagram
North End
South End
Time in Days
Slip in Inches
Deflection in Inches
0
5
10
15
20
25
30
35
0.002
0.004
0.006
0.008
0.010
0.012
0.014
0.016
0.018
0.020
0.022

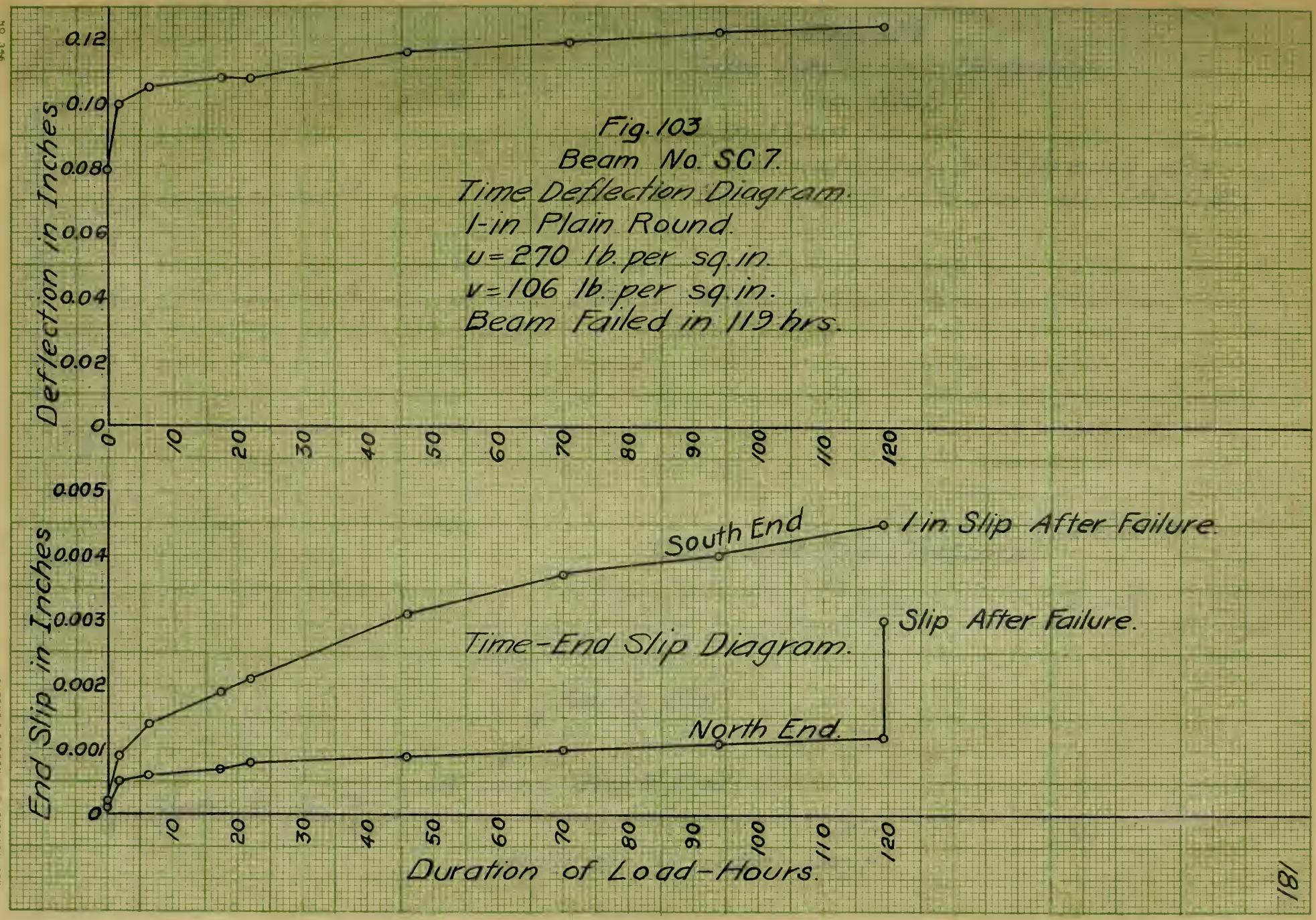


Fig. 103
Beam No. SC 7.
Time Deflection Diagram.
1-in Plain Round.
u = 270 lb. per sq. in.
v = 106 lb. per sq. in.
Beam Failed in 119 hrs.
Deflection in Inches
0.12
0.10
0.08
0.06
0.04
0.02
0
10
20
30
40
50
60
70
80
90
100
110
120
End Slip in Inches
0.005
0.004
0.003
0.002
0.001
South End
1 in Slip After Failure.
Slip After Failure.
Time-End Slip Diagram.
North End.
Duration of Load-Hours.

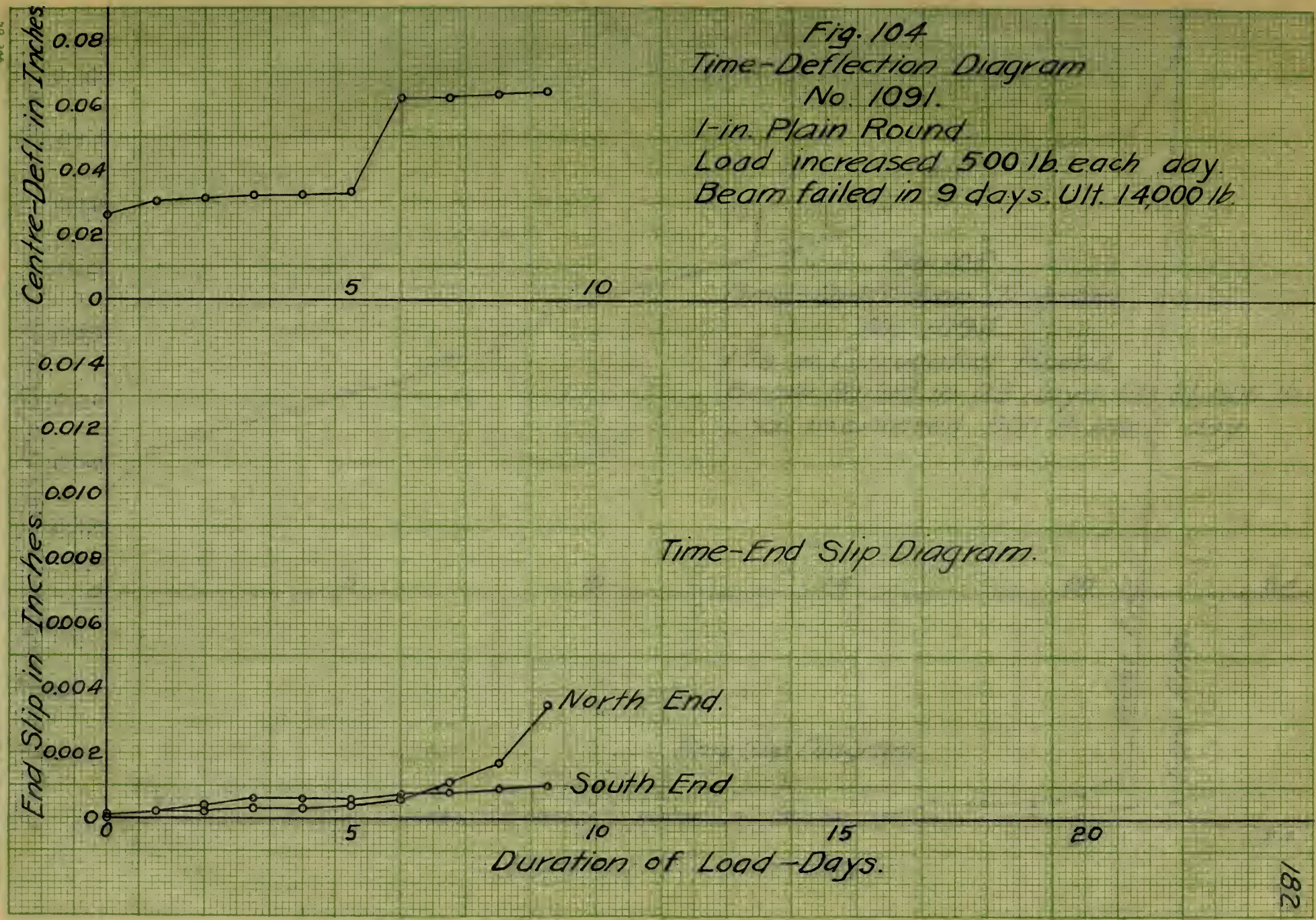
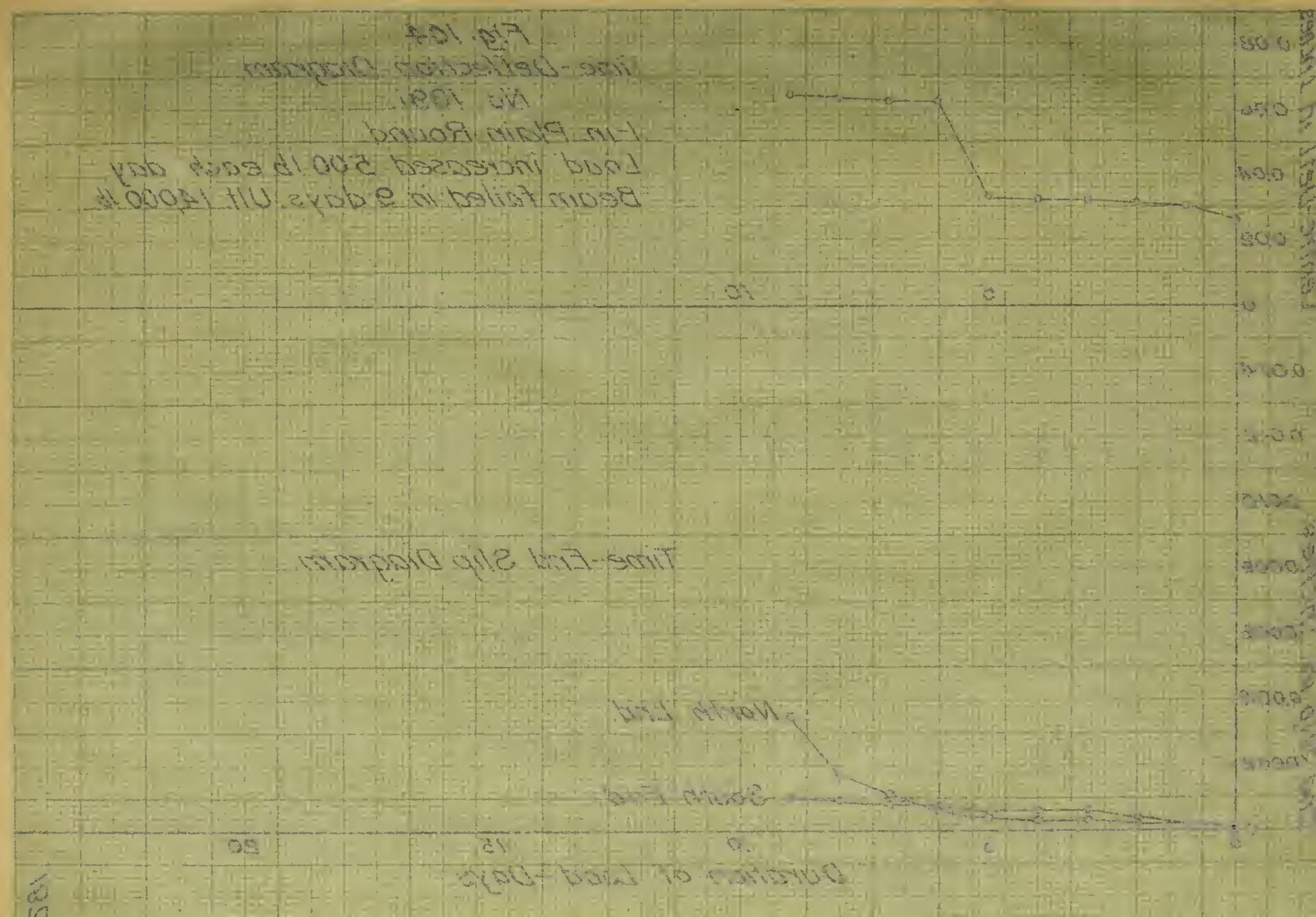
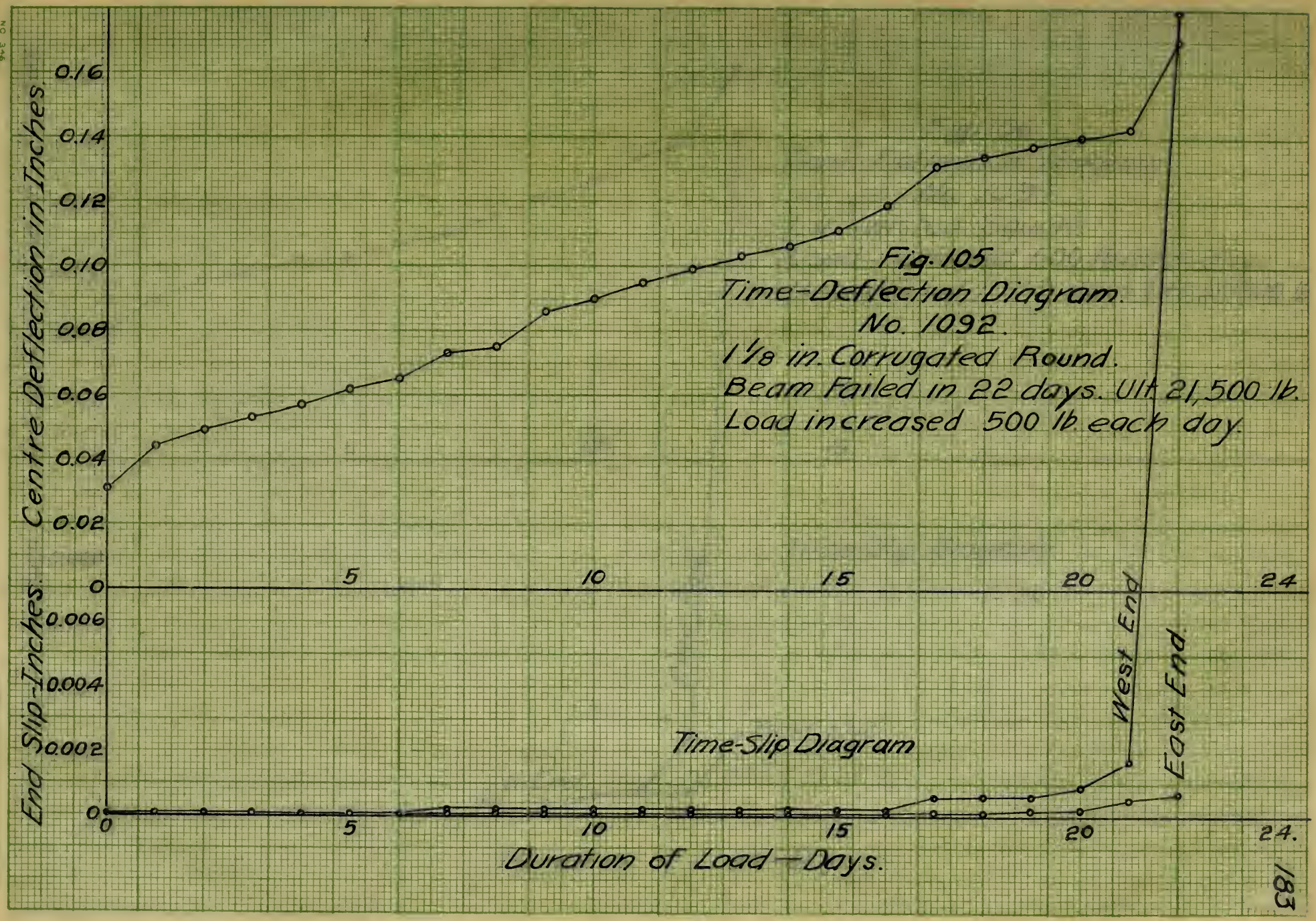


Fig. 104
Time-Deflection Diagram
No. 1091.
1-in. Plain Round
Load increased 500 lb. each day.
Beam failed in 9 days. Ult. 14,000 lb.
Centre-Defl. in Inches
0.08
0.06
0.04
0.02
0
5
10
Time-End Slip Diagram.
End Slip in Inches
0.014
0.012
0.010
0.008
0.006
0.004
0.002
0
North End.
South End
0
5
10
15
20
Duration of Load-Days.





NO 346
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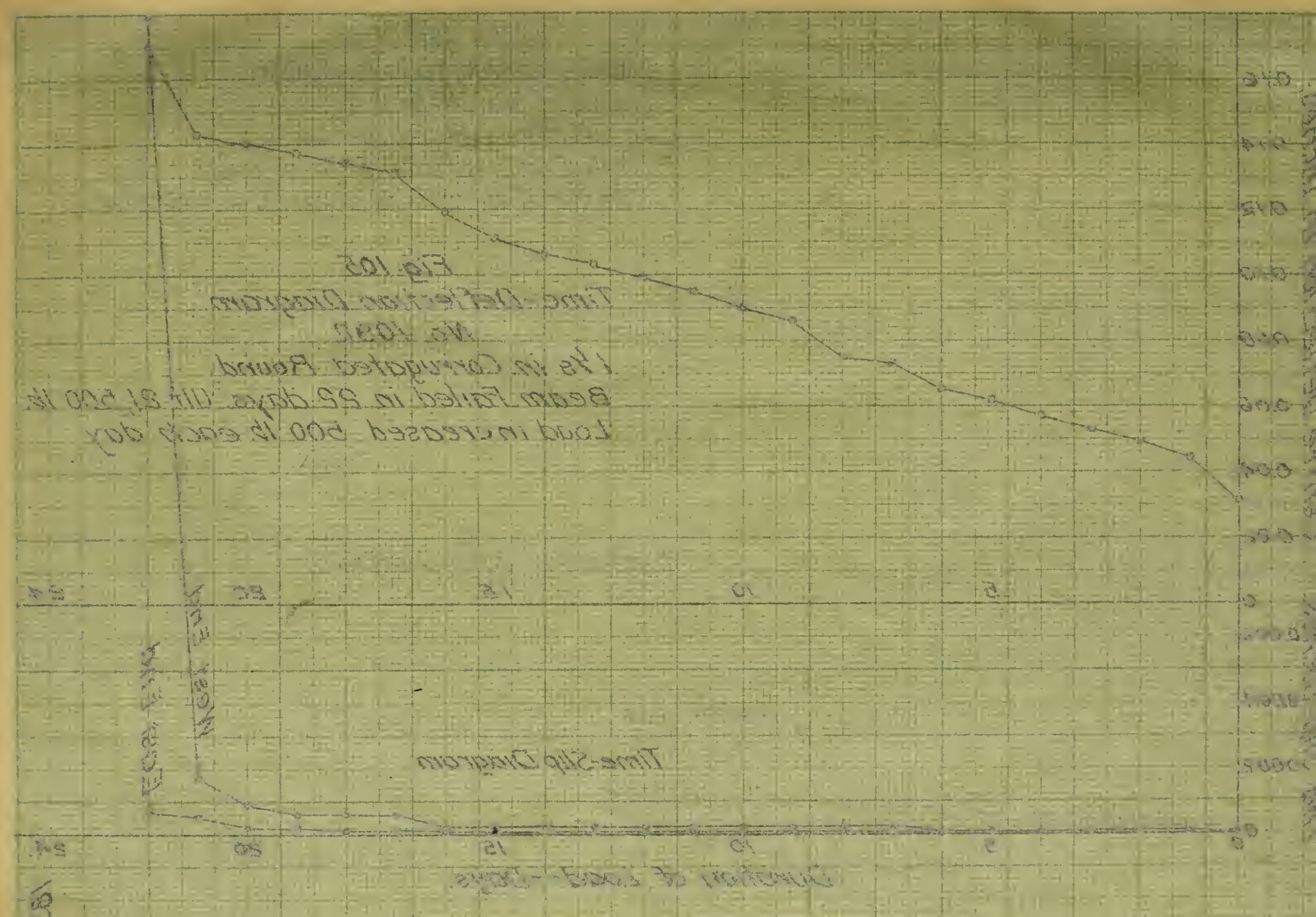
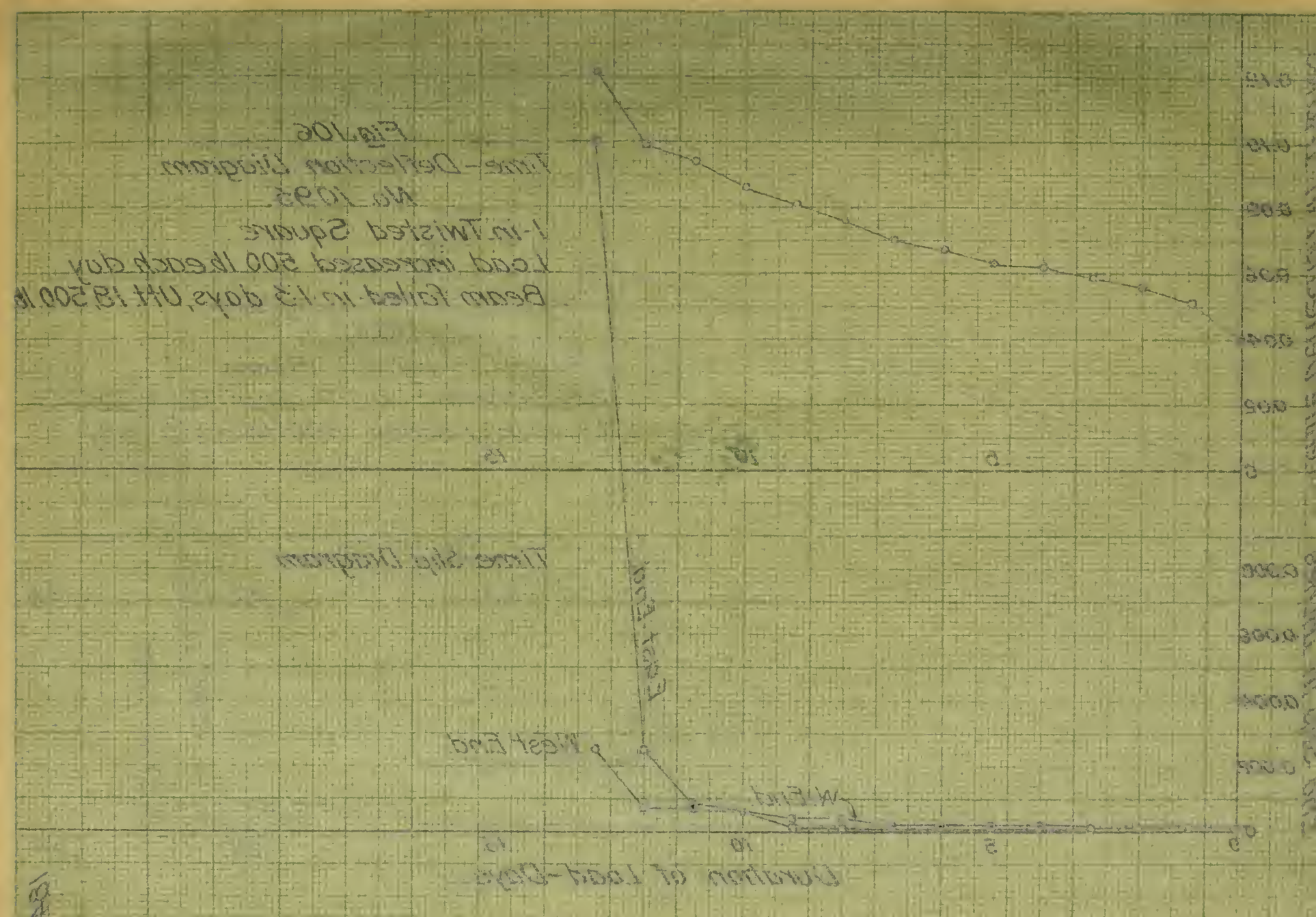
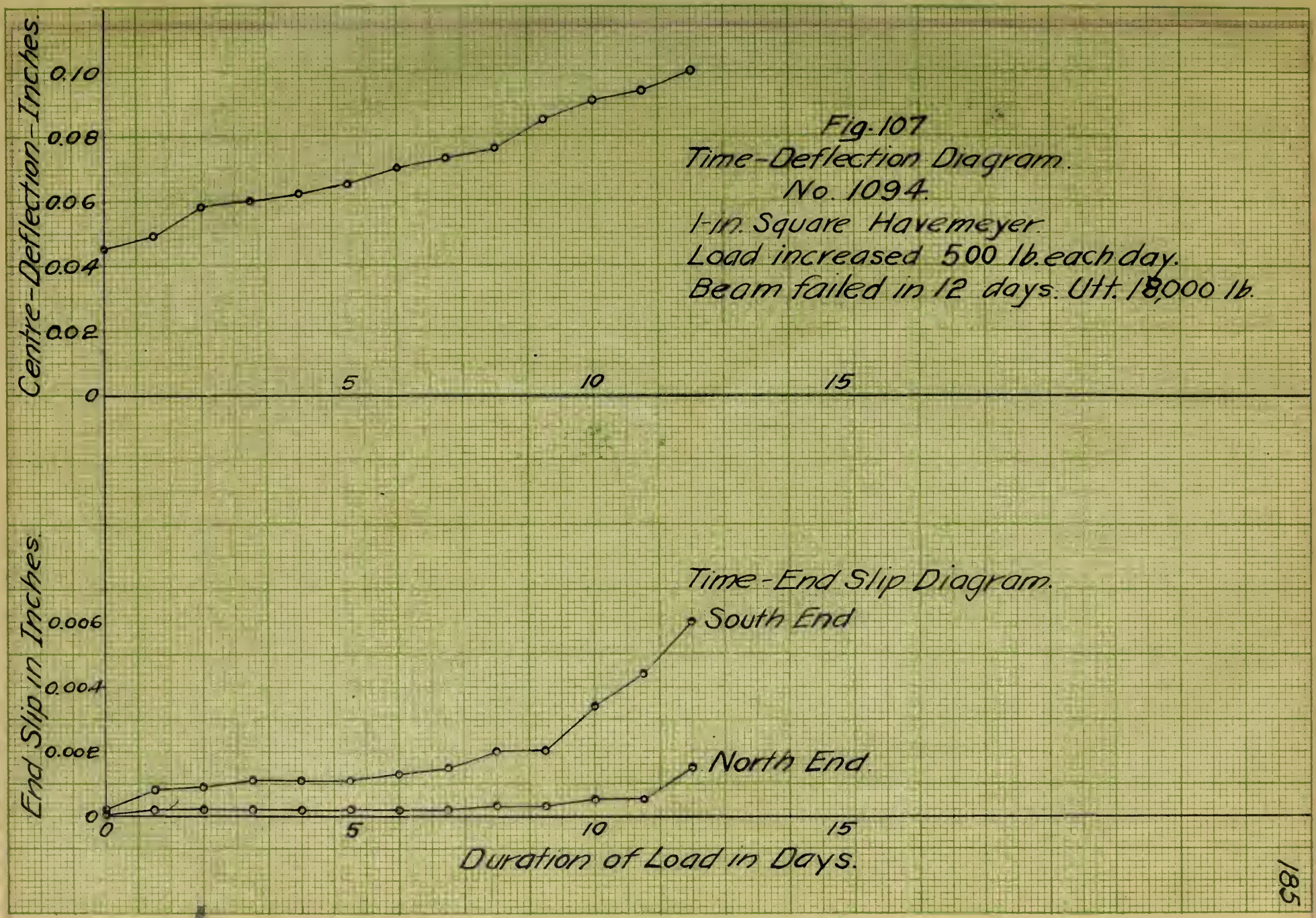
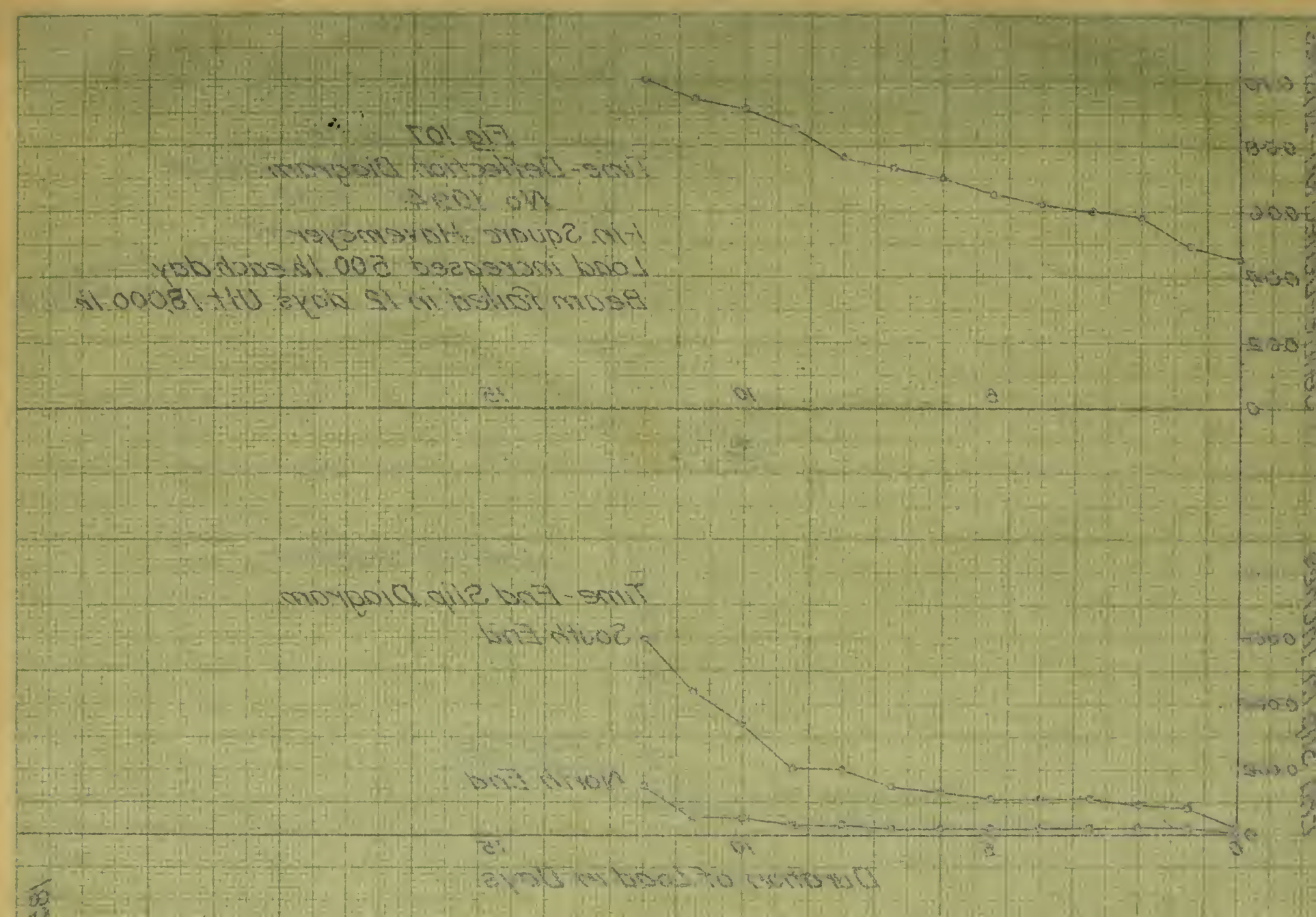


Fig. 106
Time-Deflection Diagram.
No. 1093.
1-in. Twisted Square
Load increased 500 lb. each day
Beam failed in 13 days, Ult. 18,500 lb




Centre-Deflection-Inches.
0.10
0.08
0.06
0.04
0.02
0
5
10
15
Time-Deflection Diagram.
No. 1094.
1-in. Square Havemeyer.
Load increased 500 lb. each day.
Beam failed in 12 days. Ult. 18,000 lb.
End Slip in Inches.
0.006
0.004
0.002
0
Time-End Slip Diagram.
South End
North End.
0
5
10
15
Duration of Load in Days.



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